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SINGER
SIMULATION PRODUCTS

A DIVISION OF THE SINGER COMPANY / DEVELOPER AND MANUFACTURER OF THE LINK TRAINER SINCE 1929

SHUTTLE MISSION SIMULATOR

BASELINE DEFINITION REPORT

VOLUME II December 21, 1973

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Principal Investigator
SMS Definition Study

This document is submitted in compliance with Line Item No. 8 of the Data Requirements List as Type I Data, Contract NAS9-12836

SINGER COMPANY
SIMULATION PRODUCTS DIVISION

SHUTTLE MISSION SIMULATOR
BASELINE DEFINITION REPORT

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SINGER COMPANY
SIMULATION PRODUCTS DIVISION

Preface

This document is submitted in compliance with Line Item No. 8 of the Data Requirements List as Type I Data, Contract NAS9-12836.

This document is composed of two parts, Volumes I and II.

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4.0 SOFTWARE BASELINE DEFINITION

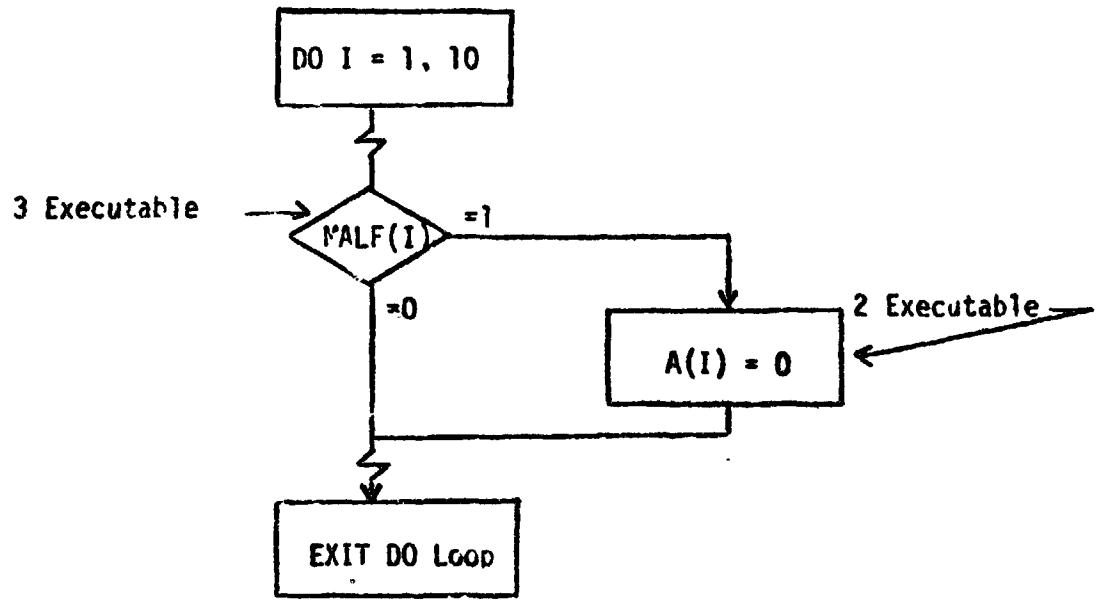
4.1 Failure Insertion Concepts

4.1.1 System Design Techniques

In many cases of simulation, the mathematical model malfunctions are added as an afterthought in the design process. Where the system has redundant components or paths, repetitive program loops are used to reduce the core requirement of the executable program. Implementation of malfunctions into these component models requires that a comparative study be made to determine the method for the least computer core and executable time requirement. In all cases it will be found that a compromise must be made between time and core. In the following four example cases, the various methods of implementation within a Do-Loop of 10 are shown with a time and core impact. In these examples a computer time of 1.5 μsec per instruction is assumed. Cases V and VI show the trade-off as was made in Skylab EPS simulation.

For purposes of clarification, the term multiple malfunction means that one data base word is used to direct a change in computational processing such that more than one segment or component may be addressed by changing of the code letter or number stored in the data base location. Cases V and VI show an example of use of "multiple malfunctions" to save time and core. Appendix A lists malfunctions applicable to the SMS.

CASE I: 10 Discrete Malfunctions Used Inside DO Loops



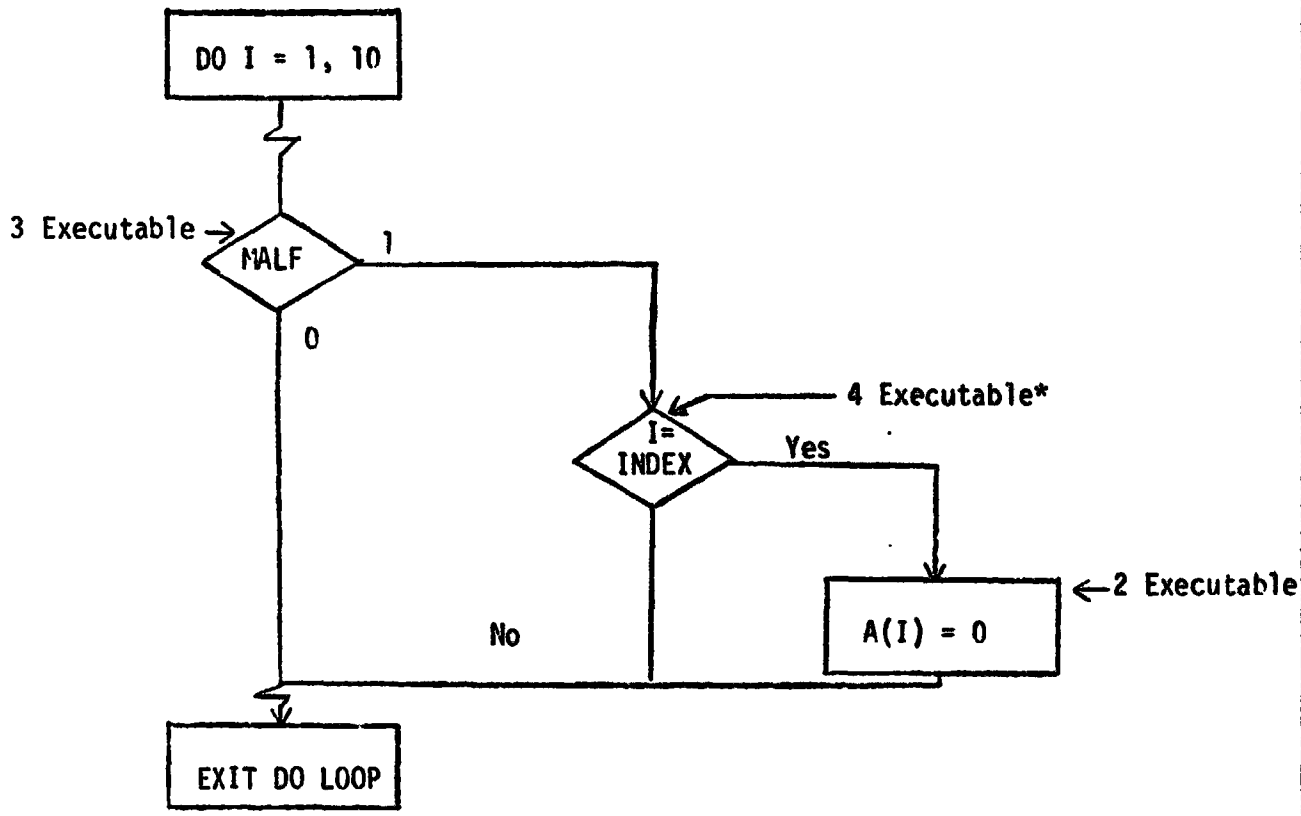
Core Summary:	Storage	Executable	Total	Bytes
	10	5	15	60

Time Summary:
Best: 3 X 10 X 1.5 = 45 μS
Worst: 5 X 10 X 1.5 = 75 μS
Nominal: 3 X 10 X 1.5 = 45 μS

Advantages:
1) All 10 malfunctions can be entered simultaneously.
2) Low execution time.
3) Easy to enter and remove via CRT.

Disadvantages:
1) High core requirement.

CASE II: One Discrete Malfunction, one malfunction index used to indicate which one of the 10 elements should be malfunctioned. All inside DO Loop.



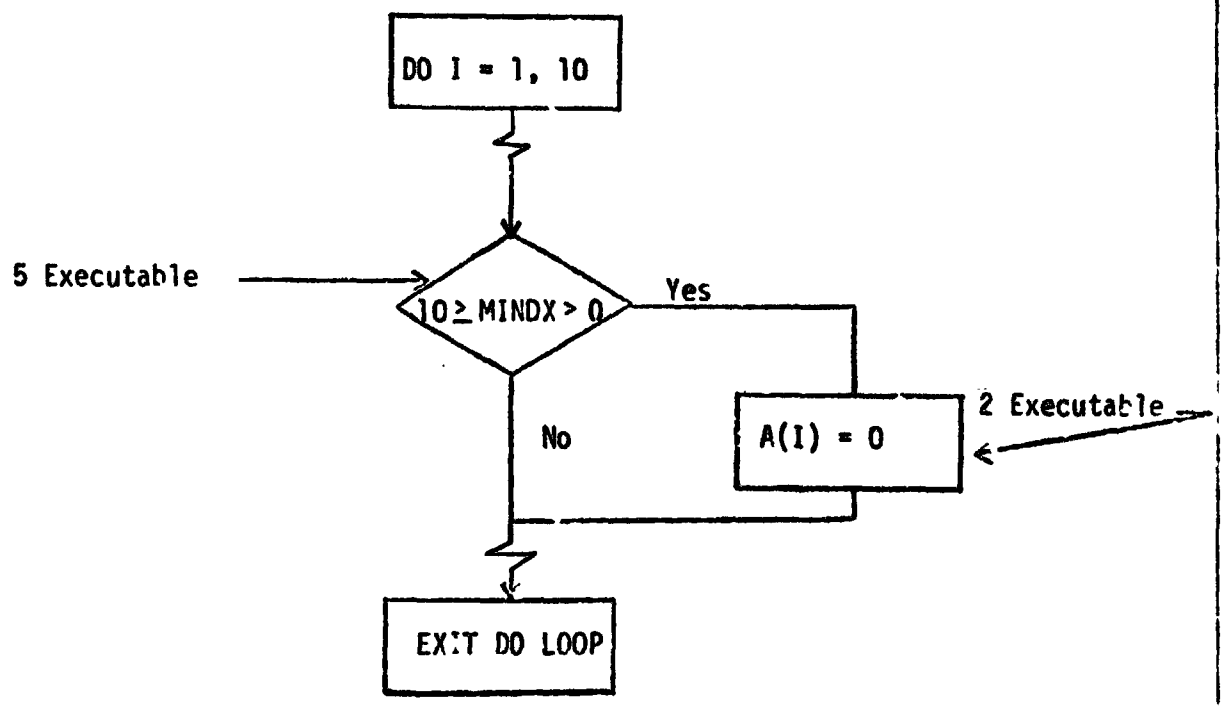
Core Summary:	Storage	Executable	Total	Bytes
	2	9	11	44

Time Summary:
- Best: 3 X 10 X 1.5 = 45 μS
- Worst: 9 X 10 X 1.5 =135 μS
- In I = Index: 9 X 10 X 1.5 =135 μS
- In I $\neq$ Index: 7 X 10 X 1.5 =105 μS

Advantages:
1) Lower Core Requirement.
2) Low time when malfunction not in.

Disadvantages:
1) High time when malfunction in.
2) Hard to enter and clear.
3) Only one malfunction may be used at one time.

CASE III: One malfunction integer location to indicate malfunction entered and specific element affected. All inside DO Loop.



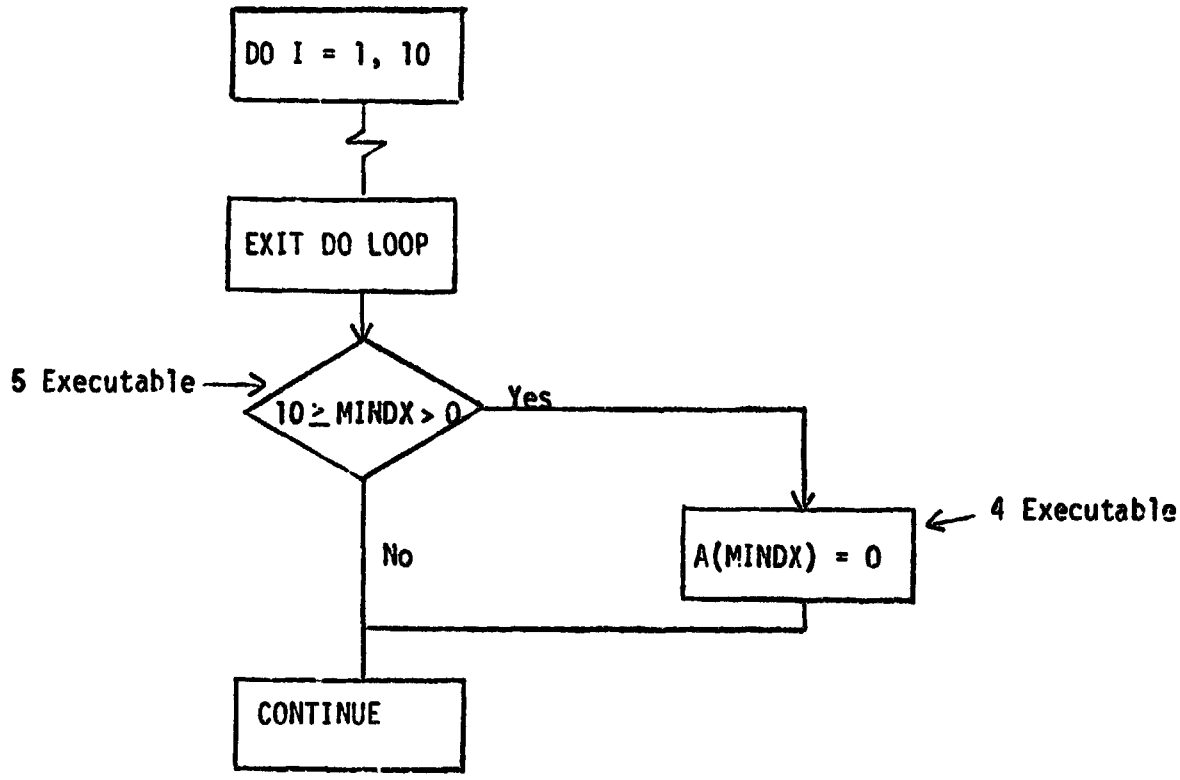
Core Summary:	Storage	Executable	Total	Bytes
	1	7	8	32

Time Summary:
Best 5 X 10 X 1.5 = 75 μS
Worst: 7 X 10 X 1.5 = 105 μS
Nominal: 5 X 10 X 1.5 = 75 μS

Advantages:
1) Low Core Requirement.
2) Easy to enter malfunction.

Disadvantages:
1) High time requirement for all paths.
2) Only one malfunction entered at one time.

CASE IV: One malfunction integer location to indicate malfunction entered and specific element affected. Malfunction programmed outside the DO Loop.



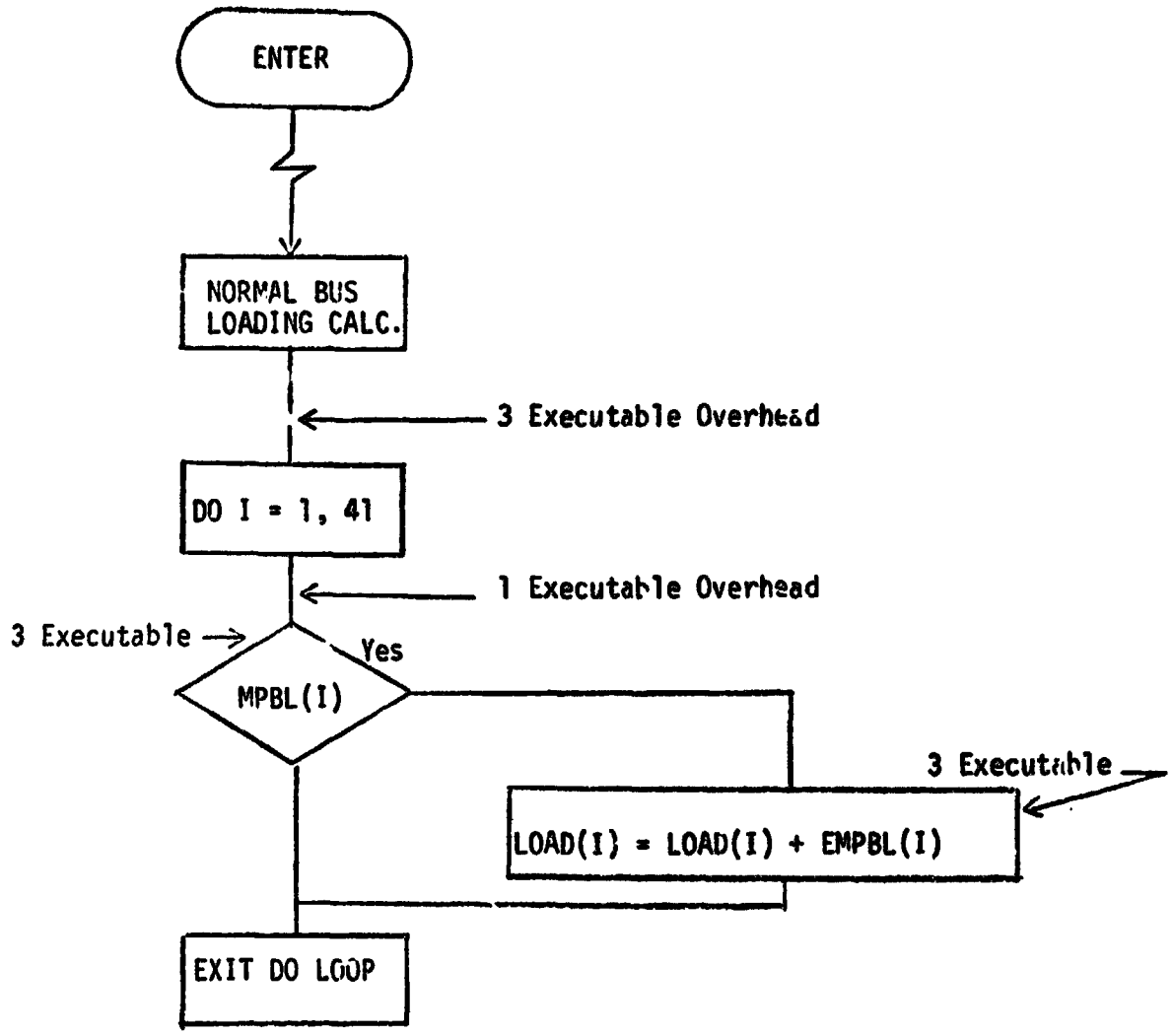
Core Summary:	Storage	Executable	Total	Bytes
	1	9	10	40

Time Summary:
Best: 5 X 1 X 1.5 = 7.5 μS
Worst: 9 X 1 X 1.5 =13.5 μS
Nominal: 5 X 1 X 1.5 = 7.5 μS

Advantages:
1) Low Core Requirement
2) Low Time Requirement
3) Easy to enter and remove

Disadvantages:
1) Only one element may be malfunctioned at a time.
2) Requires that Do Loop has ended or that additional time and core is required to do this.

CASE V: EPS Power Bus Loading Bus Overload Malfunctions. Forty-one Discrete Variable Malfunctions.



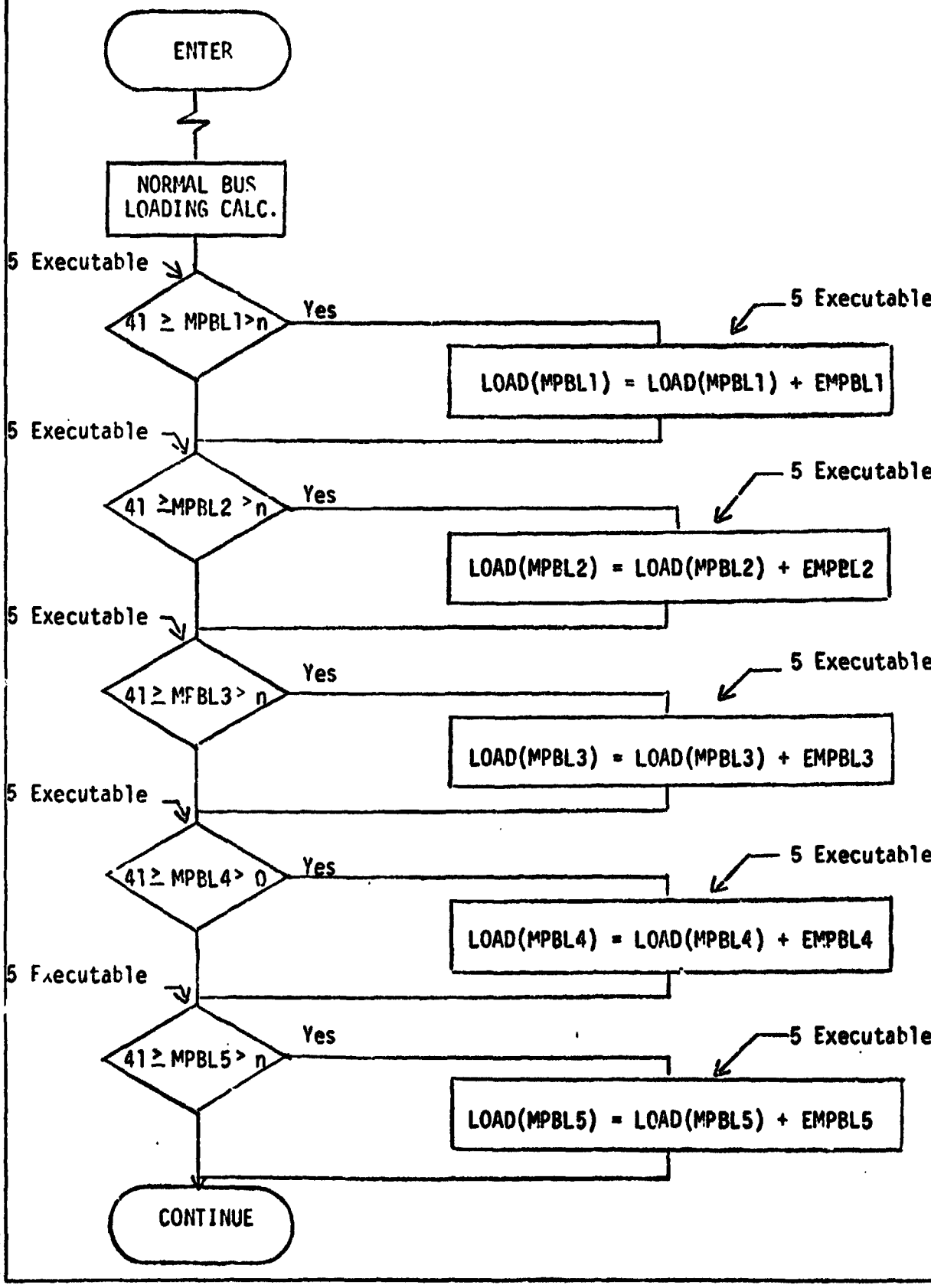
Core Summary:	Storage	Executable	Total	Bytes
	82	10	92	368

Time Summary:
Best: [3 + (4)(41)] X 1.5 = 250.5 μS
Worst: [3 + (7)(41)] X 1.5 = 435.0 μS
Nominal: [3 + (4)(41)] X 1.5 = 250.5 μS

Advantages:
1) All 41 can be entered at one time.
2) Easy to enter and remove.

Disadvantages:
1) High Core Requirement
2) High Time Requirement

CASE VI: EPS Power Bus Loading Bus Overload Malfunctions. Five Multiple Variable Malfunctions.



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Core Summary:	Storage	Executable	Total	Bytes
	10	50	60	240

Time Summary:
Best: 25 X 1 X 1.5 = 37.5 μS
Worst: 5 X 1 X 1.5 = 7.5 μS
Nominal: 25 X 1 X 1.5 = 37.5 μS

Advantages:
1) Lower Core (128 Bytes saved)
2) Lower Time (360 μS worst case, 213 μS best case)

Disadvantages:
1) Only 5 buses can be malfunctioned at one time (however, this meets the instructor's requirements).

4.1.2 Techniques of Manual Insertion

Malfunctions may be manually entered into the simulation problem in one of two ways. The first method requires that the malfunction page be selected, an available line on the page be selected, the malfunction symbol entered along with the value to be inserted into the malfunction term. Malfunctions may also be entered into the simulation problem by using the CRT keyboard. By using procedures similar to "Look and Enter" (i.e., depression of function key, entry of symbolic name, entry of value), malfunctions may be entered without selecting the malfunction page.

4.1.3 Malfunction Display Methods

Active malfunctions in the simulator may be viewed at any time by one of two methods. The first is by selecting the malfunction page. The second method involves selecting the 'active malfunction and tripped circuit breaker' page. Both pages will present a list of all current active malfunctions, and their current value.

4.1.4 Pre-Programmed Malfunctions

The insertion and control of simulated malfunctions of equipment or of variable vehicle flight conditions has required the NASA instructor to concentrate his attention on performing tasks which could be relegated to the computer. Having the computer pre-programmed to insert and/or change operating conditions will free the instructor to concentrate his efforts on those tasks the computer cannot handle such as trainee response and performance. The insertion of malfunctions through the use of a dedicated CRT page entry, similar to the existing Skylab simulation malfunction technique, may be accomplished at any time in real time mode. The automated

technique may be used to insert, display, or delete any malfunction or data base parameter by the use of pre-programmed software modules. The modules may be activated or deactivated by the instructor in real time. Display devices (CRT digital, graphics, X-T recorders, X-Y recorders) and audio cues may be activated by the use of the pre-programmed modules.

Use of this technique will allow the instructor to preplan his malfunction study program and to present identical training situations to all students. The technique also frees the instructor from having to do repetitious keyboard entry which, through human error, could lead to destruction of the training plan and computer schedule.

4.2 Flight Software

4.2.1 Simulation Requirements

4.2.2 Data Processing and Software Subsystem

The simulation of the Data Processing and Software subsystem of the Shuttle Vehicle is required to the level that all crew display data and telemetered data responses are extremely realistic for both displayed value and time response to interface signals, commands and switching logic, and simulator moding. Both the short period and long period accuracy of the simulation must be very high to maintain astronaut confidence in the simulated system and avoid negative training in the use of the system. This will be particularly true during M.C.C. integrated mission training where outputs of the ground computer system are compared with the calculations made in the simulator. Hence the requirement for use of actual OBC flight programs, and an accuracy no less than that of the actual on-board computers. In this case, a 32-bit computer should be utilized for the simulation.

As a minimum, the actual crew station display and control equipment should be used in the simulator to ensure high fidelity display and control. This should include the dual redundant tape readers, if crew procedures dictate the requirement for loading and operating these d .ices.

The simulated Data Processing and Software subsystem must also interact with the simulator mode functions without degradation.

The reset function in the simulator is provided to enable rapid return and restart at mission time points where extensive training is required while skipping over time periods of low activity.

The astronaut should be able t select the active and standby primary computers, and switch to the Rackup GN&C computer and realize the same effects as in an actual flight. The requirement to simulate redundancy effects occurs in conjunction with the requirement for simulated malfunctions to train in all backup

modes of operation. Simulated malfunctions should be chosen based on failure analysis of real world equipment coupled with the desire to train the astronauts in all backup modes and highly critical procedures to ensure their safety in all real flight.

Use of actual OBC flight software is necessary for reasons of simulation fidelity and to avoid delays inherent in the functional simulation software development and test/verification processes. It is anticipated that software changes to the primary GN&C OBC programs will occur with very short notice. Therefore, the simulator software should be capable of being rapidly updated and reverified, and any equipment or software required to expedite this operation should be provided.

4.2.3 Main Engine Controller

The simulation of the Main Engine computer programs should be of equivalent accuracy, resolution, and iteration rate as in the real world. Data rates and formats to recorders and to the Telemetry system must be simulated with high fidelity.

The main engine computer simulation must interact with the simulator mode functions without degradation.

Simulation of the redundancy features is also desired to enable training in backup modes and procedures by inserting malfunctions of one or more elements of the engine controllers.

Selected elements of each engine controller will be malfunctioned to provide crew and MCC training in backup modes and procedures.

4.3 Applications Software Conceptual Design

4.3.1 Power Systems

4.3.1.1 Electrical Power Subsystem

The Electrical Power Subsystem may be generally divided into six problem areas requiring math models. These are power interface, switching logic, bus loading, power generation and storage, power distribution, and control and display. For the shuttle vehicle there are three types of electrical power having distinct requirements for simulation. These are the DC subsystem, the single phase AC subsystem, and the three phase AC subsystem. Each of these subsystems interface with the others through electrical loads or by providing power sources. The concept presented here describes the subsystems separately with interfacing parameters between subsystems.

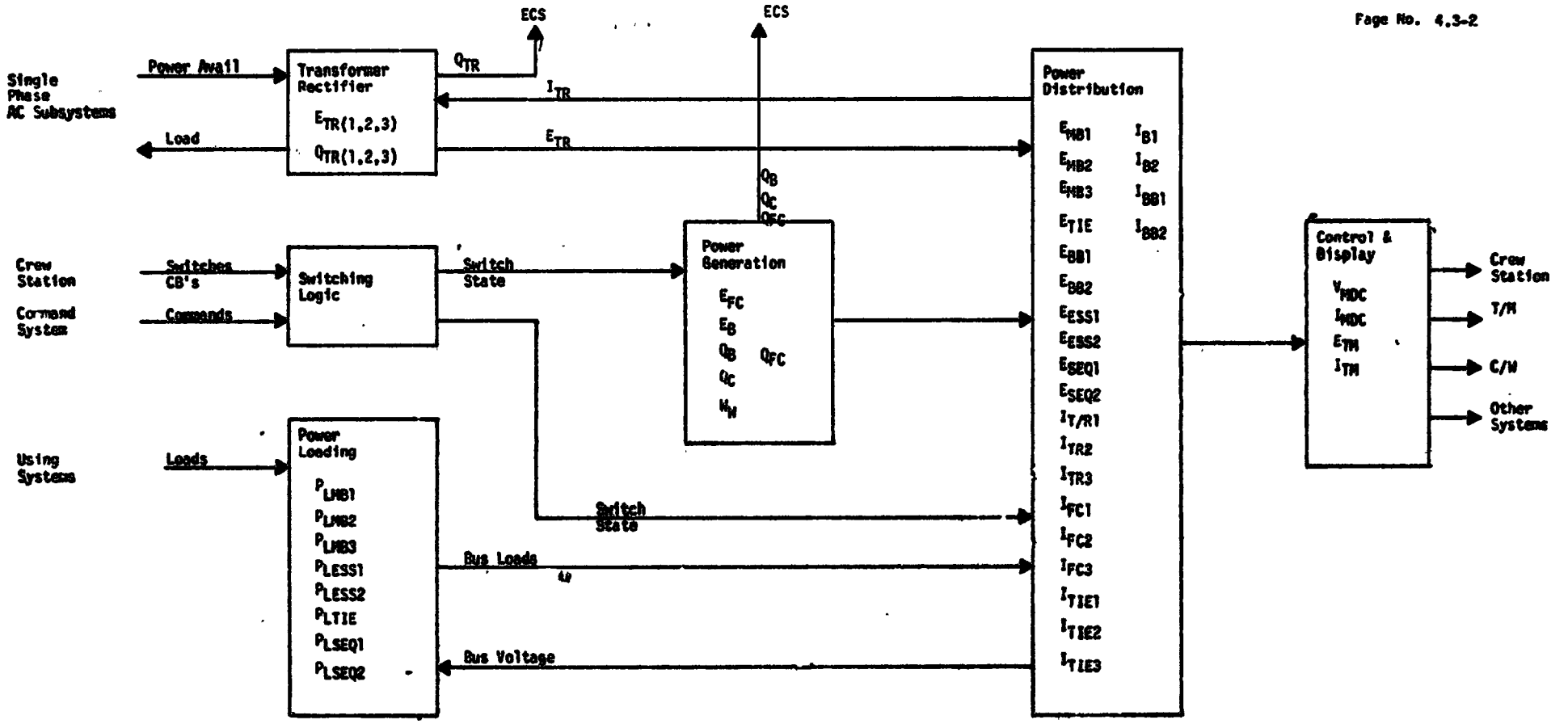
Figure 4.3.1.1.1 shows the proposed groups of equations required for the DC subsystem network. The DC subsystem has fuel cells, batteries, and transformer-rectifiers supplying power to three main DC buses, two battery buses, two essential control buses, and two sequencer buses. Because of malfunction consideration, the tie bus must also be considered as a load bus.

The transformer-rectifier equations provide the output voltage from each unit as a function of the electrical load current. A power available boolean will be made available by the single phase AC subsystem for each transformer-rectifier and, in turn, each transformer-rectifier will calculate electrical loads for the single phase AC subsystem. Load sharing will be accomplished by varying the T-R output voltage as a function of the electrical load. Curve fits to test data will be used for this function. Heat generated by the T-R unit will be calculated for the ECS Subsystem and ECS will calculate the unit temperature.

(1) T-R Output voltage

$$E_{TR} = f(I_{TR})$$ current and temperature limited function.

4.3.1.1.1 DC POWER SUBSYSTEM



(2) T-R Heat generated

$$Q_{TR} = f(E_{TR}, I_{TR}, Eff)$$

The power loading equations provide summations of all electrical loads on the DC buses. Individual loads below 3 watts are handled as a gross load under control of the instructor. So that variations in loads under different voltages can be accounted for, a straight line curve fit is computed to calculate the load as a function of the bus voltage.

(3) Electrical Load summation

$$PLMB1 = \text{Loads} \cdot K_{\text{voltage curve}}$$

where E_{TR} = Voltage of Transformer Rectifier unit

I_{TR} = Current out of Transformer Rectifier unit

Q_{TR} = Heat generated in Transformer Rectifier unit

Eff = Efficiency of unit

P_{LMB1} = Load in main bus 1

K = Coefficient of slope of voltage/power curve

The power generation equations calculate the voltages of the storage batteries and the fuel cells and the heat and water by-products.

(4) Battery Voltage

$$B_{SOC} = f(B_{SOC}, B_{TEMP}, Eff, I_B)$$

$$E_B = f(B_{SOC}, B_{TEMP}, I_B)$$

(5) Battery Heat generated

$$Q_B = f(I_B, Eff)$$

(6) Charger Heat generated

$$Q_C = f(I_C, Eff)$$

where: B_{SOC} = Battery state of charge

B_{TEMP} = Battery temperature

Eff = Efficiency of battery current conversion

I_B = Current out of battery

E_B = Battery terminal voltage

Q_B = Battery heat generated by current flow

Q_C = Charger heat generated by current flow

The generation of power by the fuel cells requires that the inlet conditions of reactants be tightly controlled. Simulation of the oxygen and hydrogen supply also requires modeling the gaseous nitrogen pressurant supply. In Figure 4.3.1.1.2 a general flowchart of the software interfaces is shown. The valve and control logic equations model the real world system response to crew station switch and circuit breaker position with electrical power available. Display parameters are generated for valve repeater flag states.

Valve position is used by the Nitrogen System equations to calculate the pressure exerted on the cryogenic liquids. The heat absorbed by the two cold fluids will be used to calculate the volume of liquid and volume of gas in the cryogenic tanks. A heat balance model will be developed for the exchange of heat/temperature with the ECS subsystem. Gaseous oxygen usage will be simulated for the atmospheric model simulation of ECS. Refer to Section 4.3.7.3 for the method of simulation of conductive and radiative heating.

The usage of oxygen and hydrogen will be computed by empirical formula:

$$O_2 = K_1 \times I \text{ lbs/hr.}$$

$$H_2 = K_2 \times I \text{ lbs/hrs.}$$

where O_2 = oxygen mass flow rate

H_2 = hydrogen mass flow rate

K_1, K_2 = empirical constants

I = electrical current

The electrical potential will be reduced by a lower nitrogen pressure differential than nominal for the cell. In addition the electrical potential will be increased with increasing operating temperature. Both of the functions will be curve fitted approximations to performance data.

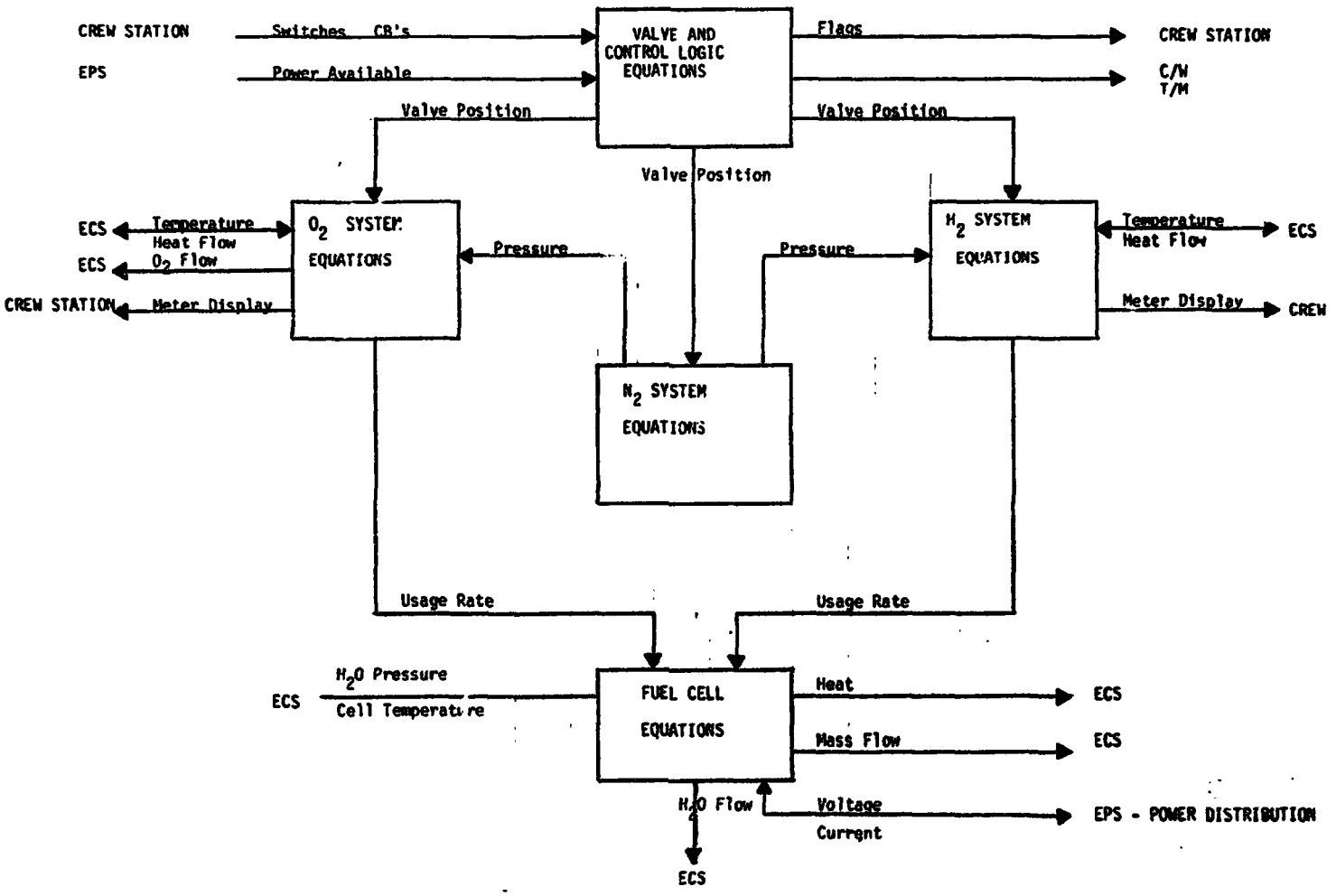


FIGURE 4.3.1.1.2 FUEL CELL SYSTEM

The power distribution equations will calculate the voltage of each major bus and the currents to or from the bus. The mathematical approach is the nodal analysis method which was used on the Skylab Simulator. This method gives an explicit solution to the bus voltage calculations. Using the bus voltages it is then possible to calculate all interbus currents from the voltage differential and the conductance.

The general form of the nodal equation solution is in the form:

$$E = f\frac{\Sigma V \cdot G}{\Sigma G}$$

where: E = Node voltage

V = driving source voltage

G = Conductance in nodal network

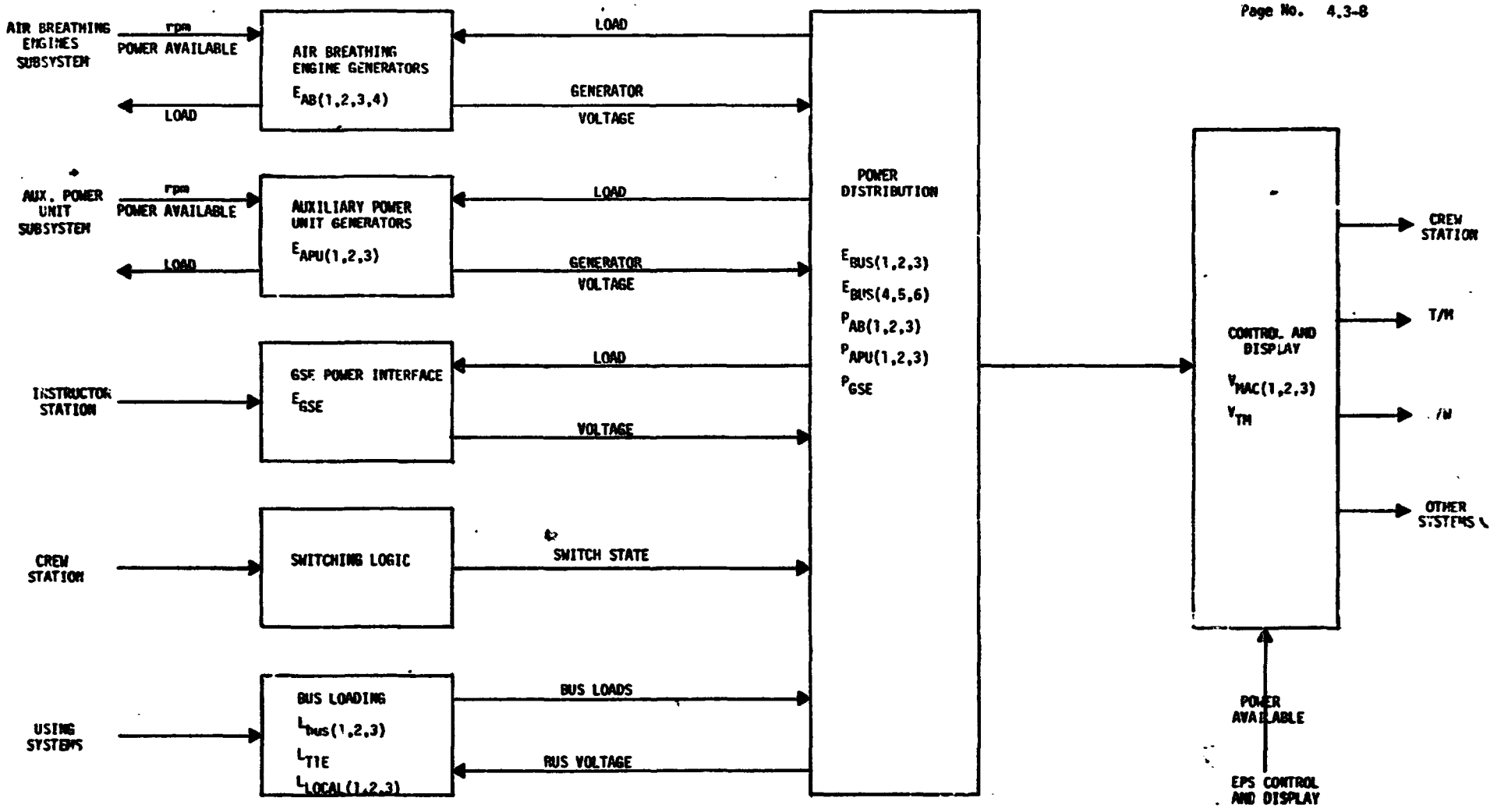
Figure 4.3.1.1.3 shows the proposed groups of equations required for the simulation of the single phase AC subsystem network.

The power sources for this network are the Air Breathing Engine generators, the APU generators, and the GSE power. For the purposes of simulation, the loads are assumed to have an overall power factor of 1.0. It is also assumed that the generators cannot be brought into sync for load sharing between units.

The Air Breathing Engine generator equations give the output frequency as a function of the generator rpm. The voltage output of the generator will

FIGURE 4.3.1.1.3

SINGLE PHASE AC SUBSYSTEM



be a function of both rpm and the power load. Since the frequency is not displayed but is probably supplied to Caution and Warning as an out of tolerance condition, only a boolean expressing the frequency condition will be generated.

$$E_{AB} = f(rpm, load)$$

$$W_{AB} = f(rpm)$$

The generators driven by the APU are basically the same as the Air Breathing Engine except that both frequency and voltage may be controlled by the generator control unit through speed and field control.

$$E_{APU} = f(rpm, load)$$

$$W_{APU} = f(rpm)$$

The GSE power interface will be by instructor control for simulating mating cable connections and for power source supply voltage and power.

The switching logic equations calculate the state of the power control relays as a function of crew switch, circuit breaker position and up-link commands. The switch state is provided to the power distribution program to establish path conductances.

The bus loading equations provide summations of all electrical loads on the single phase AC buses. Small loads below 3 watts are to be handled as a composite load variable by instructor control.

The power distribution equations will calculate the voltage of each major bus and the total load on each source generator. Under the assumptions that the power factor for the overall loads is 1.0 and the generator cannot be in sync, the solution reduces to the equation:

$$E = \frac{V\ G}{G_1 + G}$$

$$P = VEG_1$$

Where: E = Bus voltage

V = Source voltage

G = line conductance, source to bus

G_1 = load conductance

P = Power consumed

The Control and Display equations use the booleans generated by the DC control and display equations to condition parameters for crew display, Caution and Warning, and telemetry programs.

Figure 4.3.1.1.4 shows the general equation groups required for simulation of the three phase AC subsystem. The subsystem simulation is very similar to the single phase subsystem with one significant difference. Loss of a single phase will not cause shutdown of the equipment in the three phase subsystem as it would do in the single phase subsystem. Where one phase is out in the three phase subsystem, the two supporting buses will reflect increased loading.

For simulation purposes the loads on each leg are assumed to have an overall power factor of 1.0. For the three phased subsystem, it is assumed that the units sync immediately from the master sync line of the selected unit.

The sources of three phase power are the four static inverters, each capable of supplying the master sync and three phase power. Each inverter may be connected to a maximum of two bus sets. It is assumed that an inverter will fail safe on loss of the input sync signal. A boolean will be generated for a frequency out-of-tolerance condition if required by the Caution and Warning or Telemetry programs. The output voltage on each leg of the inverter is a function of the leg load.

$$E_{INV(A,B,C)} = f(load)$$

FIGURE 4.3.1.1.4

THREE PHASE AC SUBSYSTEM

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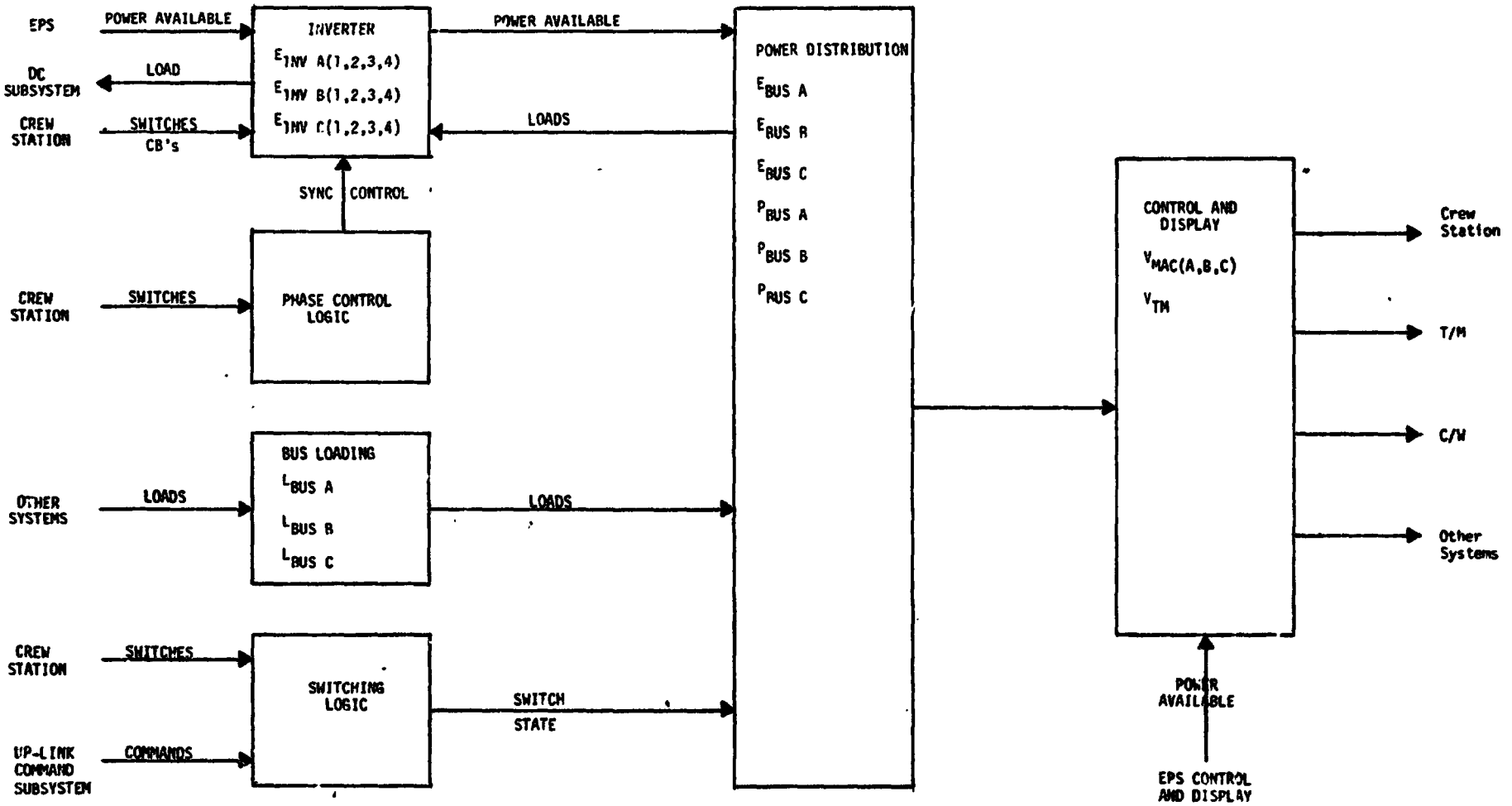


The bus loading equations supply a summation of the loads on each bus leg. The switching logic equations calculate the switch and relay state based on switch, circuit breaker, and up-link command logic.

The power distribution equations will calculate the voltage of each major bus and the load on each inverter unit. Under the assumptions stated, the power distribution equations reduce to:

$$E_{BUSA} = \frac{V_1G_1+V_2G_2}{G_1+G_2+G} \qquad \text{(Typical)}$$

$$P_{1BUSA} = (V_1-E_{BUSA})G_1 \qquad \text{(Typical)}$$

where: E_{BUSA} = Bus voltage (Phase A shown)

V_1 = Inverter #1 Voltage (Phase A)

V_2 = Inverter #2 Voltage (Phase A)

G_1 = Line conductance, inverter 1 to bus

G_2 = Line conductance, inverter 2 to bus

G = Load conductance, Phase A.

P_{1BUSA} = Power to Bus A from inverter 1, Phase A

The control and display equations to be used by the three phase subsystem are combined with the single phase subsystem outputs. The reason is only one crew station display is provided for the AC voltages.

The computer will provide control over circuit breakers during periods of simulated high currents. Upon calculation of an overcurrent of 150% of the circuit breaker rating, the circuit breaker will be set open. The circuit breaker control routine of the control and display equations will also provide simulated defective circuit breakers which cannot be reset and hold. Malfunctions will also be provided for intermittent shorts causing circuit breaker opening.

The equations of the EPS simulation will be repeated for each unit either by programmed loops or repetitive equations, whichever design uses the least amount of time and core. The required malfunctions for the EPS simulation will be designed into the equations for minimum computer impact.

4.3.1.2 Auxiliary Power Unit Subsystem

The Auxiliary Power Unit simulation will be divided into six basic areas of equations. See Figure 4.3.1.2. These mathematical representations of the real world system could be written in engineering equations which may be derived. Engineering equations are normally required for simulation where systems are highly instrumented. At present, however, the crew has minimum controls and displays relating to the APU operation. All control inputs apparently actuate automatic sequencer logic for both start up and shutdown of the turbines. Since the crew also has minimum displays, realistic functional equations will be written to generate the required display parameters with a minimum impact on computer time and core loading.

The shaft loading equations will calculate the mechanical loads on the turbine engine. Inputs to the program will be provided by the Hydrualic System and the Electrical Power System. The loading equations are to include the effect of friction and windage and the lube pump load.

$$L_S = (L_H + L_E + L_{LP} + L_K)/K_{eff}$$

where L_S = Shaft load on turbine

L_H = Hydraulic loads

L_E = Electrical loads

L_{LP} = Lube pump loads

L_K = Friction and windage loads

K_{eff} = Mechanical efficiency

The control logic equations are to provide simulation of valve state as the result of crew switch and circuit breaker inputs. Timing delays are to be incorporated only where the response would be detected by the crew.

The Helium pressurization simulations will calculate the amount of helium (pressure, temperature, mass) in the pressurization bottles and the pressure in the hydrazine tank. The gaseous volume and gas pressure will be calculated using the fuel quantity remaining in the hydrazine tank.

$$V_H = V_T - V_F$$

$$M_H = P_H V_H / R T_H$$

where V_H = Volume of helium

V_T = Volume of fuel tank - constant

V_F = Volume of fuel

P_H = Pressure of helium

M_H = Mass of helium

R = Universal gas constant

T_H = Temperature of helium

and

$$M_{HP} = M_o - M_H$$

$$P_{HP} = M_{HP} R T_{HP} / V_{HP}$$

where M_{HP} = Mass of helium in high pressure tank

M_o = Mass of helium - originally in tank - constant

P_{HP} = Pressure of helium - high pressure tank

T_{HP} = Temperature of helium - high pressure tank

V_{HP} = Volume of high pressure helium tank - constant

The fuel equations will provide not only the fuel quantity integration but the supply pressure to the gas generator. These equations are to take into account valving between the fuel tanks and the gas generator.

$$P_F = P_H$$

$$Q_F = Q_F - Q_C$$

where P_F = Pressure of fuel on gas generator

Q_F = Fuel quantity remaining

Q_C = Fuel quantity consumed

The gas generator equations will include logic and functional transforms simulating the generation of gas. The gas generator equations will include conditional parameters for valve state to the turbine engine control valves. Electrical power usage will be calculated for EPS bus loading.

$$G_G = f(t_{H,}\ P_F)$$

where G_G = Gas generation

t_H = Heater warm-up time

The turbine engine equations will calculate the functional engine speed, exhaust temperature, and fuel consumption rate based on the shaft loads. Power available booleans are also to be provided to the subsystems of Electrical Power and Hydraulic Power. Start up and shutdown sequences are to be functionally simulated.

$$R_{pm} = f(G_{G,}\ P_{F,}\ L_{s,}\ t_s)$$

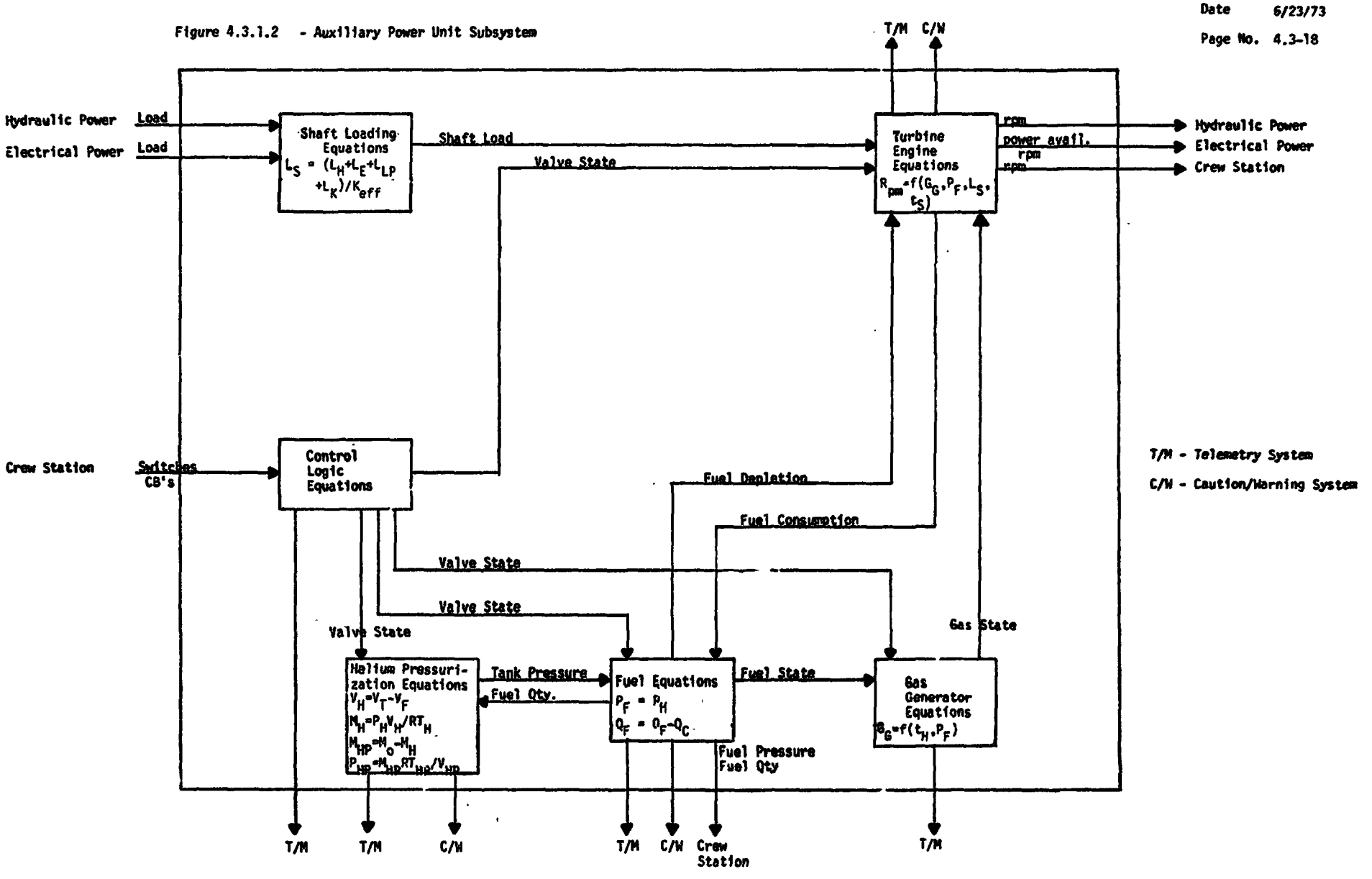
where R_{pm} = Turbine R_{pm}

t_s = time from start-up or time from start of shutdown

From these groups of equations, parameters simulating the actual system state will be conditioned using sensor and display logic booleans from the Electrical Power System for crew station display, for input to the Caution and Warning System, or for input to the Telemetry Multiplexer Program. The equations will be repeated for each auxiliary power unit, either by programmed loops or

by repetitive equations, whichever requires the least amount of computer time and core. Required malfunctions for the APU are to be designed into the simulation for minimum computer impact.

Figure 4.3.1.2 - Auxiliary Power Unit Subsystem



T/M - Telemetry System

C/W - Caution/Warning System

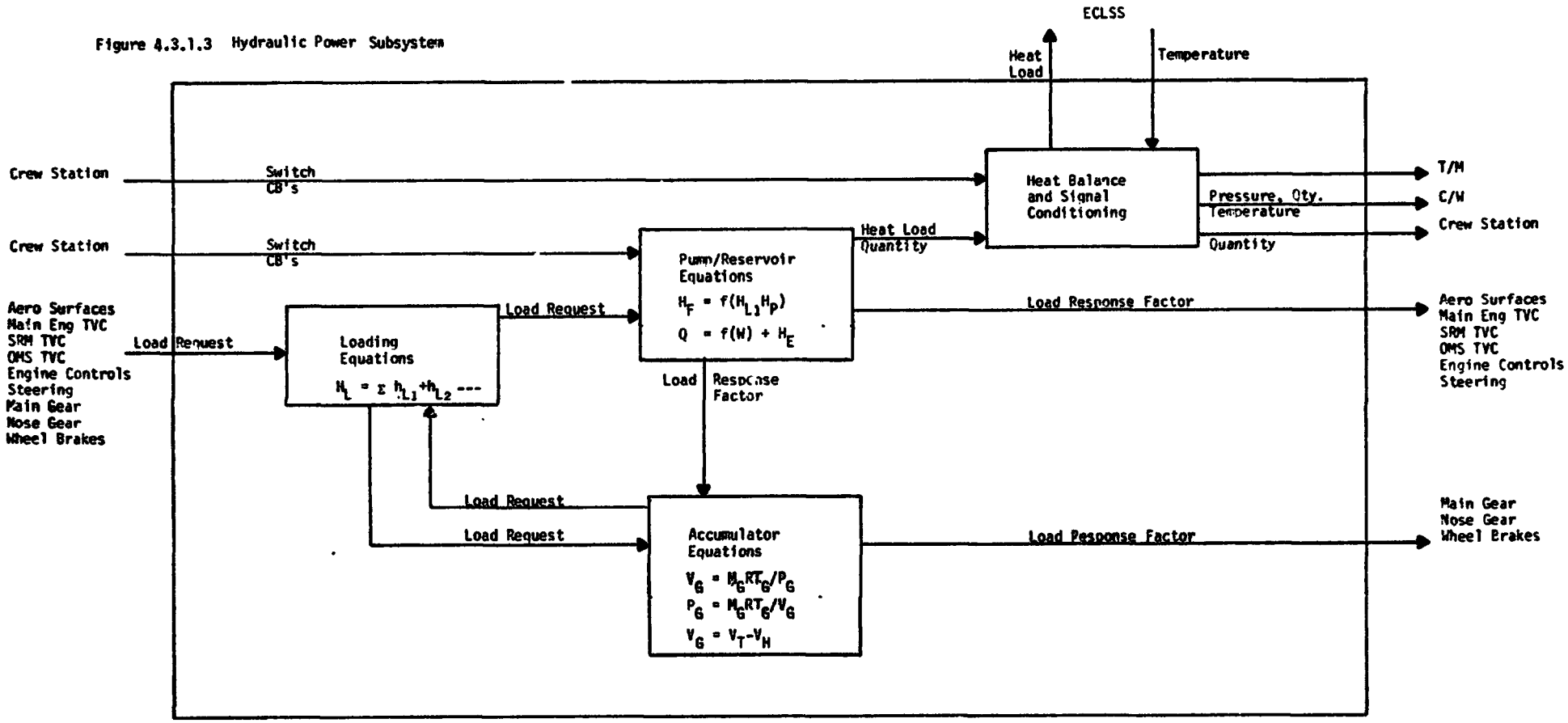
4.3.1.3 Hydraulic Power Subsystem

The Hydraulic Power Subsystem will be divided into four blocks of gen ally related equations for simulation purposes. Figure 4.3.1.3 shows the interfaces of these equation groups. The mathematical equations used as representative of the real world system could be derived engineering functions, however, the crew station controls and displays are minimal. At present, the crew displays are limited to hydraulic fluid temperature and quantity. Caution and Warning displays relate to high and low fluid temperature, low fluid quantity, and low pressure. Realistic functional equations will be written to generate the required display parameters without an excessive computer time requirement.

Two of the hydraulic power using subsystems, Aerodynamic Control Surfaces and Thrust Vector Control, require large quantities of fluid. Interface requirements, as the result of the servo loop hydraulic system, dictate that the Hydraulic System simulation of load versus power run at the same iteration rate as these subsystems (or twenty to ten iterations per second). This requirement, in addition to the minimum displays, justifies the functional approach to simulation of this system.

The loading equations will calculate the summation of the fluid flow from the four main supply lines. The program will also calculate flow from the main supply lines to the two accumulators. These fluid flow summations form load request parameters for the pump-reservoir equations and the accumulator equations. The load request parameters are to be generated by the using systems for elevons, rudder-speed brake, main engine TVC, engine controls, OMS TVC, SRM TVC, gear uplock, gear deployment/retraction, wheel braking, steering, RCS door operation, and payload bay doors.

Figure 4.3.1.3 Hydraulic Power Subsystem



$$H_L = \Sigma H_{L1} + H_{L2} \cdots$$

Where H_L = hydraulic load on supply main-gpm

H_{L1}, H_{L2} = individual load requests.

The accumulator equations will simulate the stored power by calculating a load response factor for all units that use accumulator hydraulic pressure. This load response factor is a function of the mass, temperature, and volume occupied by the entrapped gas. The volume occupied by the gas will be calculated by a summation of hydraulic fluid usage and resupply for the accumulator. Load requests will be generated by the equations for use in the loading equations as hydraulic fluid is used from the accumulator.

The limit of the pressure within the accumulator is set by the hydraulic supply.

$$V_G = M_G R T_G / P_G$$

Where P_G = Pressure on accumulator gas or hydraulic pressure if it exceeds internal accumulator pressure.

M_G = Mass of gas in accumulator

T_G = Temperature of gas in accumulator

V_G = Volume of gas in accumulator

R = Universal Gas Constant

The volume occupied by the gas is the volume of the accumulator tank less the volume of hydraulic fluid.

$$V_G = V_T - V_H$$

Where V_T = Accumulator tank volume

V_H = Volume of hydraulic fluid in the accumulator.

During the expansion cycle the pressure in the accumulator is expressed by

$$P_G = M_G R T_G / V_G$$

The pump-reservoir equations are to simulate the four sources of power to each manifold supply pipe. The pumps are the two APU gear pumps, the ABPS gear pump, and the AC driven circulation gear pump. Simulation logic will be incorporated to prevent back flow into these pumps where check valves exist. Relief and by-pass valves will be logically represented for equation usage. A summation of total pump capability will be made to furnish a load response factor for using subsystems based on load request. Reservoir quantity will be calculated from a summation of pump usage-return fluids to the reservoir.

During simulation in real time, the load response factor will allow using subsystems to react in a realistic maneuver when an hydraulic flow (or load) request is made which exceeds the capability of the pump (or pumps) on-line to supply the volume of fluid requested at the design pressure.

The time response of systems is computed by a load response factor or a factor expressing the percentage of the requested load that was supplied by overloaded pumps.

$$H_F = f(H_L, H_P)$$

or

$$H_F = \left(\frac{H_L}{H_P}\right)$$

Where the hydraulic load H_L is less than the total pump capability on the manifold, the response factor H_F will be set to 1.0. If the load request exceeds the pumping capability, the hydraulic load response factor is calculated by dividing the total requested hydraulic load by the pumping capability. Each using subsystem may then calculate the percentage of motion achieved at the low volume flow and then recalculate a new hydraulic load request.

A heat load is to be calculated for heat balance equation usage to determine the temperature of the hydraulic fluid. The calculation of temperature of the hydraulic fluid will take into account coolant valve positions as the result of crew switch, circuit breaker, and electrical power conditions. Interface parameters of heat load on the water boiler heat exchanger will be calculated for use by the ECS Subsystem simulation. The ECS Subsystem will calculate a return fluid temperature for use by the heat balance equations.

The heat added to the hydraulic fluid is calculated by the amount of work or electric energy added.

$$Q = f(W) + H_E$$

Where Q = heat added

W = work done on hydraulic fluid

H_E = electrical energy added

From these groups of equations, parameters simulating the actual system state will be conditioned using sensor and display logic booleans from the Electrical Power System for crew station display, for input to the Caution and Warning Subsystem, or for input to the Telemetry Subsystem Multiplexer Program. The equations will be repeated for each hydraulic pump and manifold supply pipe, either by programmed loops or by repetitive equations, whichever requires the least amount of computer time and core. Required malfunctions for the Hydraulic System are to be designed into the simulation for minimum computer impact.

Heat balance, sensor, signal conditioning, and temperature calculations will be accomplished on an iteration rate of five or two per second by internal program logic.

Pages 4.3-24 thru 4.3-39 left blank intentionally.

4.3.2 Propulsion System

4.3.2.1 Main Engine Simulation

A Main Engine System functional simulation is shown in Figure 4.3.2.1-1 with the major program functions and the general interfaces. The simulation model will accept crew station switch and circuit breaker status and internal switching logic to determine valve and display position. Electrical power available will be provided by the EPS simulation. The ECS simulation will be provided with base heating rates for thermal modeling as required. Telemetered data and inputs to the C/W model will be provided. Controller computed engine status will be interfaced to the GNC computer to provide correct simulation fidelity for those required functions.

The simulation of the main engine by a functional model may be used to represent the real world system with a high degree of accuracy. The intent of the design is to use the engine model developed by NASA MSFC with minor modifications so as to allow the simulation to run in real time. The simulation will use multiple digital computers. The interfacing computer between the GNC computer and the main computer will execute at a basic frame rate of 25 iterations per second. This rate matches the basic GNC rate. The interfacing computer will execute the functions of the main engine controller required by the GNC and the main engine functional model. Those functions associated with internal checks will not be executed. The interface computer will also compute these equations of the functional engine model which require high iteration rates (i.e., 10 and above). These equations are primarily associated with the Engine Performance Equations. Refer to Figure 4.3.2.1-3. The programs requiring an iteration rate of five per second or less will be accomplished in the main computer. These programs are the Helium Storage Tanks, Helium Pressurization Manifold, and the Propellant Tank Equations.

The next sections describe the Main Engine Functional Simulation and the Controller Functional Simulation. Interfacing parameters are listed in the Appendix. These tables are extracted from NASA referenced documents.

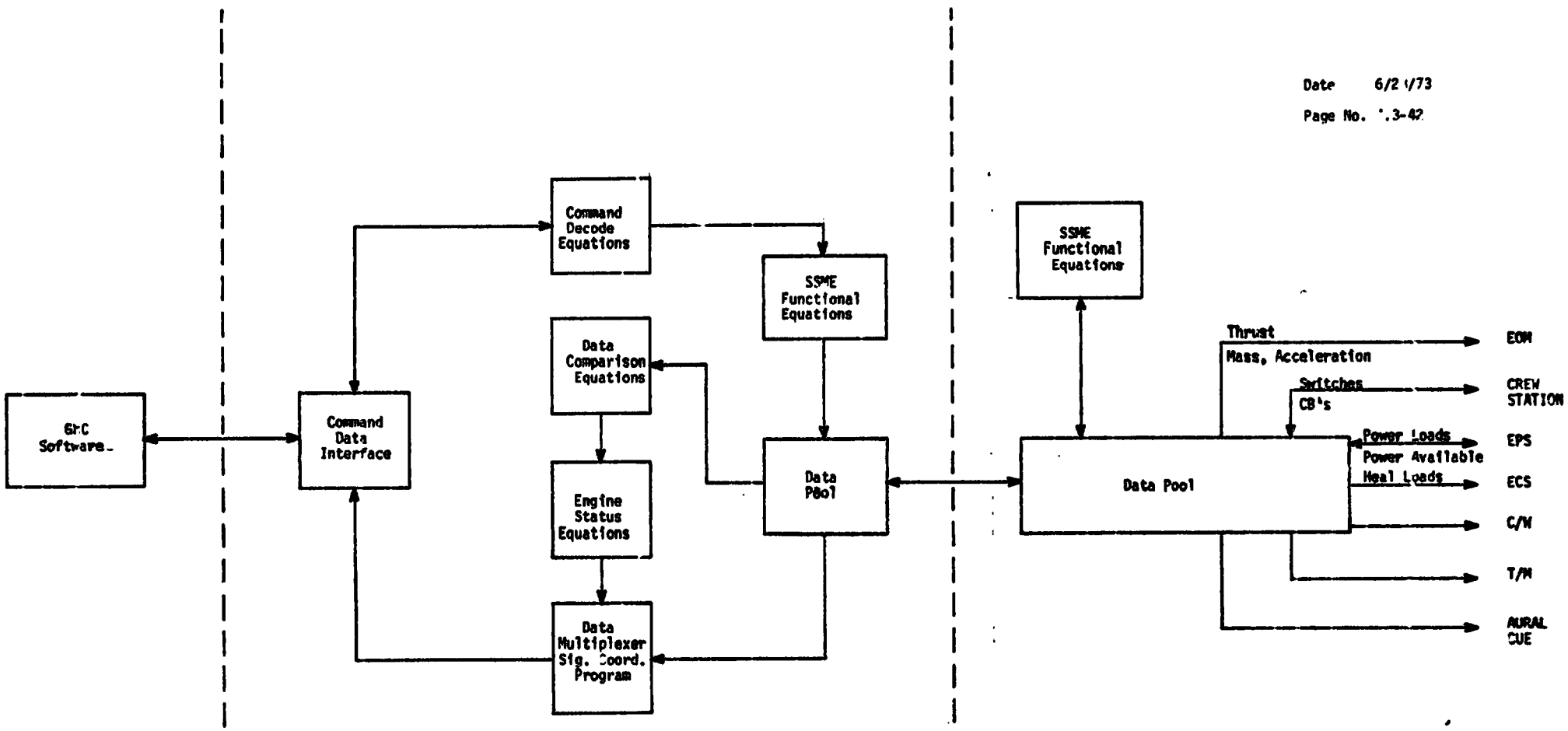


Figure 4.3.2.1-1 SSME Simulation Interfaces

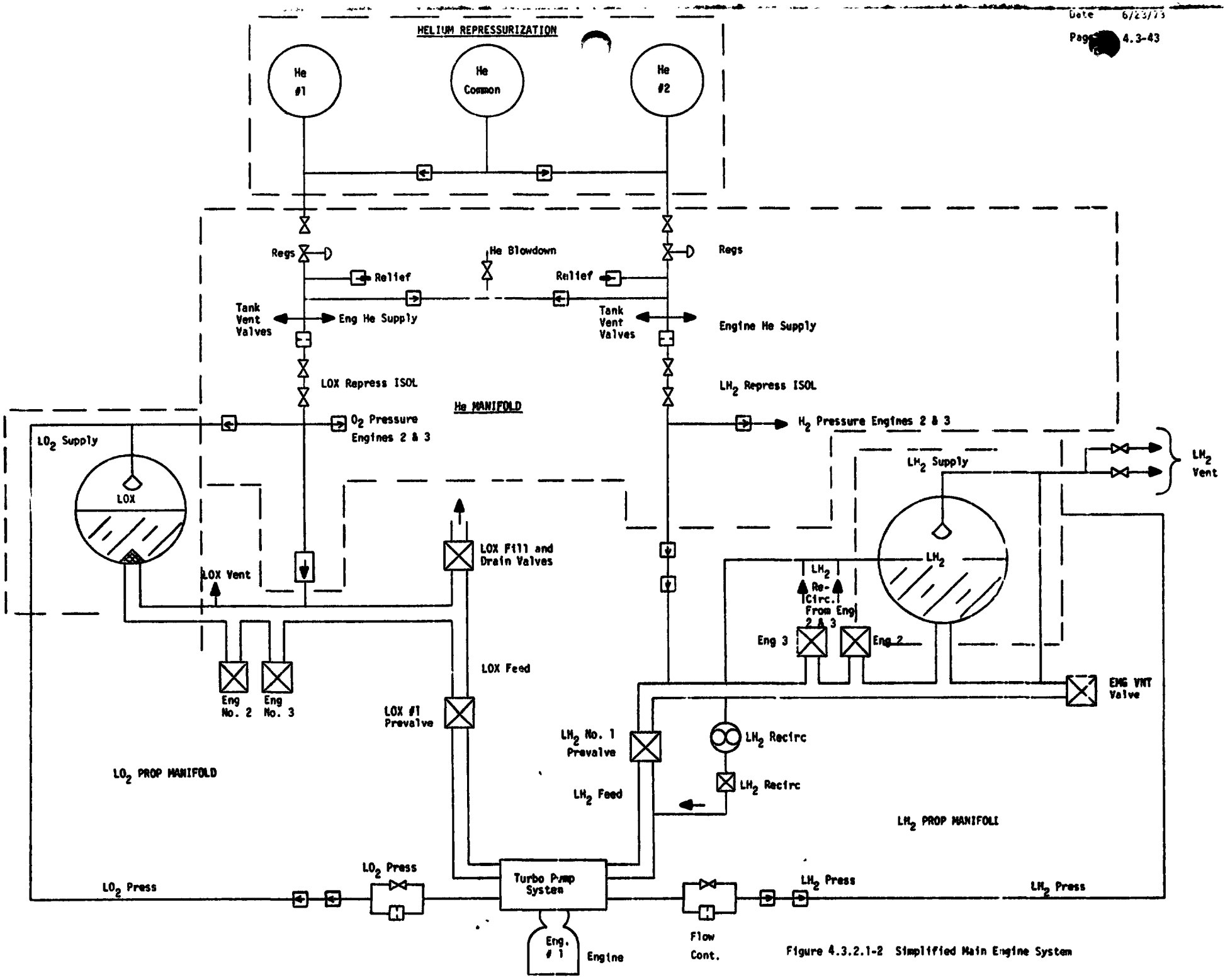


Figure 4.3.2.1-2 Simplified Main Engine System

This section describes the general form of equations used to represent the different processes of the SSME system. The conceptual design for the SSME simulation model has been formulated using basic process descriptions as system building blocks.

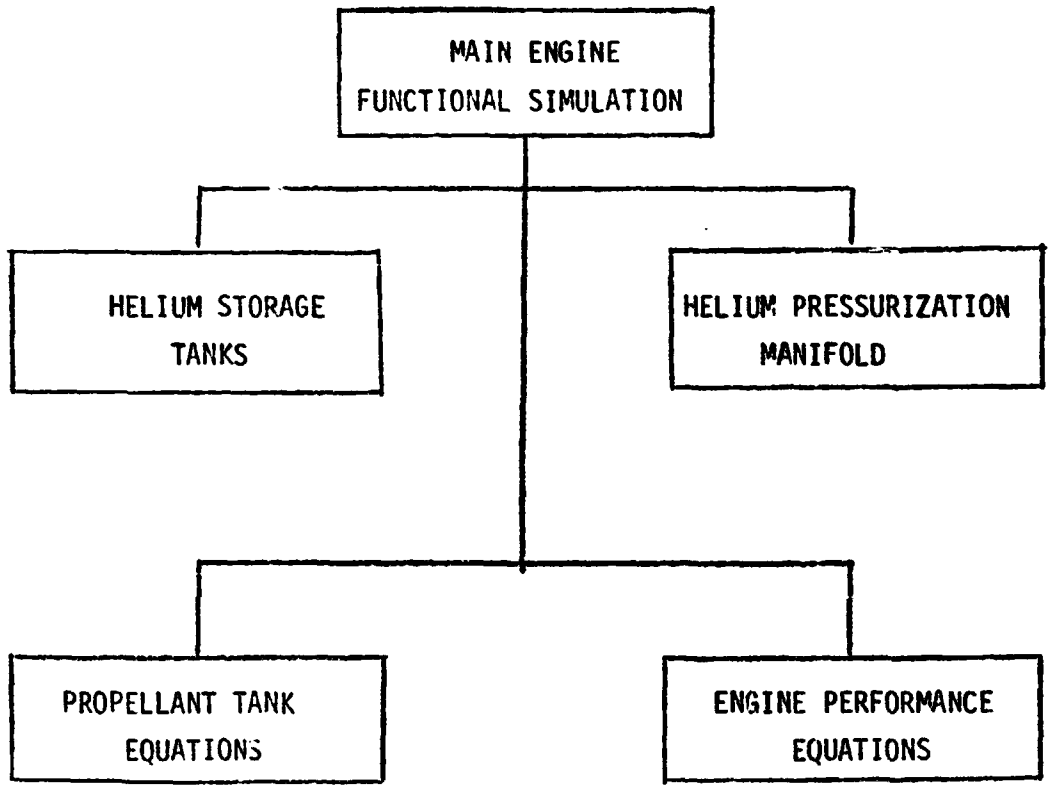


FIGURE 4.3.2.1-3

Helium Storage Tanks

A 4,000 psi helium storage system with 750 psig regulation capability is provided in the orbiter for valve actuation and engine helium requirements. During re-entry and recovery, the MPS fluid system will be repressurized with helium to preclude the entrance of contamination into the system.

The system is comprised of three storage tanks, No. 1 He, No. 2 He, and COMMON He. No. 1 Helium system is used to repressurize the LO_2 propellant system and No. 2 Helium system is used for the LH_2 system. The COMMON Helium tank provides helium to both No. 1 and No. 2 systems through a common manifold.

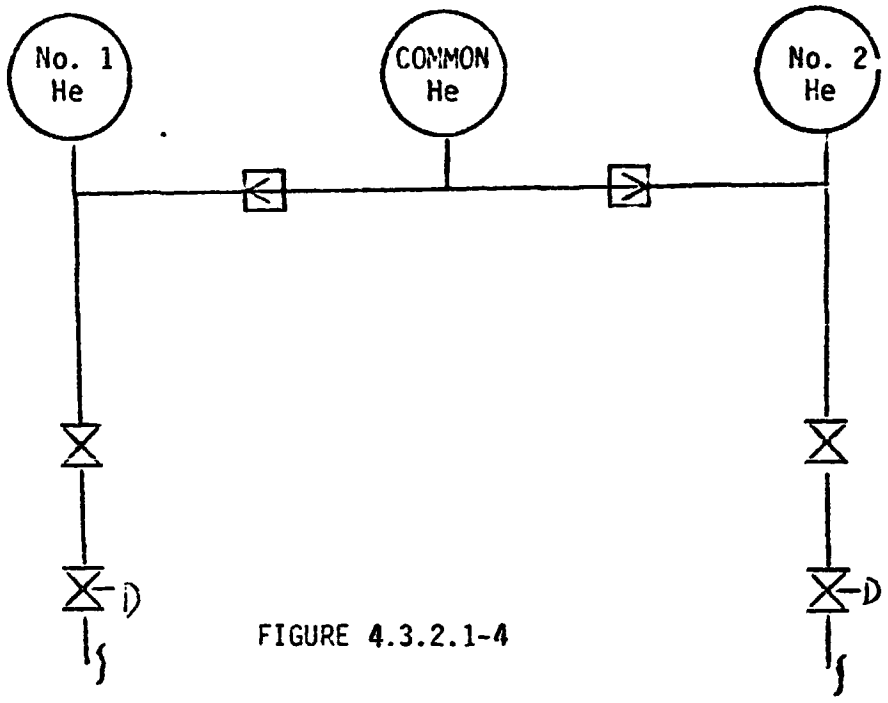


FIGURE 4.3.2.1-4

The initial gas storage pressure P_i for a tank may be expressed as:

$$P_i = \frac{R(T_i + 460)}{\left(\frac{V_t}{wHe_i} - \beta\right)} \quad 144$$

where: R = Helium Gas Constant - 386 ft/^{o}R

T = Temperature of Helium - ^{o}F

V_t = Tank Volume - Ft.^{3} - Constant

WHe_i = Initial Helium Weight - pounds

β = Non-perfect gas correction factor - function of temperature

Initial values for Helium weight and temperature would be provided through simulator initialization (reset).

Helium weight would be computed from:

$$WHe_n = WHe_{n-1} - \int \dot{W}H_e \, dt$$

Helium temperature would be computed from

$$T_{He_n} = \int \left[\frac{-(\frac{R}{J}) \ (T_{n-1} + 460)\dot{W}He + K_t(Ta - T_t)}{C_v \ WHe_n} \right] dt$$

where: T_{He_n} = Helium temperature - present iteration

$T_{He_{n-1}}$ = Helium temperature - last iteration

$\dot{W}He$ = Weight flowrate of helium out of tank

WHe_n = Weight of Helium - present iteration

J = Joules' Constant - 778 $\frac{ft - lb}{BTU}$

K_t = Effective thermal conductivity of helium tank - BTU/min - ^{o}F

Ta = Ambient temperature of Helium tank

T_t = Internal temperature of Helium tank

C_v = Specific heat of helium at constant volume - BTU/lb - ^{o}F

Helium Pressurization Manifold

Helium flowrates out of the helium storage tanks can be computed from the simplified equation for compressible fluid flow in a line having resistance, R_ℓ, measured from Point 1 to Point 2:

$$\dot{W}He = \sqrt{\frac{P_1 - P_2}{R_\ell}}$$

R_ℓ is computed for each helium line and would have the units

$$\frac{min^2}{in^2 lb}$$

Simulated flowrates will be controlled by discrete logic developed to simulate valve, regulator, and helium free path conditions.

The pressure at any point, x, in the helium manifold can be computed from the pressure upstream of Point x (i.e., the regulated outlet pressure) minus the pressure drop at Point x.

$$P_x = P_{ro} - \left(\dot{W}He_x\right)^2 R_\ell$$

where R_ℓ is the resistance of the line from the regulator to Point x.

It is anticipated that temperature for any point in the helium manifold is not a simulation requirements since this parameter is not monitored by the flight crew.

Propellant Tank Equations

Propellant Temperature

The fuel (LH_2) and oxidizer (LO_2) temperatures will be computed from initial temperature versus time tables

$$T_{fu} = f_1(\text{time})$$

$$T_{ox} = f_2(\text{time})$$

Ullage Pressure and Temperature

The ullage pressure at any time can be expressed as a simple function of the total mass, total volume, average temperature, and average molecular weight of the tank gas, and the universal gas constant.

$$P_u = \frac{m_{tg}\, T_{tg}\, R}{V_{tg}\, M_{tg}}$$

The values for m_{tg}, V_{tg}, T_{tg}, and M_{tg} may be obtained at any time from the following rate equations:

$$m_{tg} = m_{tg_i} + \int \dot{m}_{tg}\, dt$$

$$V_{tg} = V_{tg_i} + \int \dot{V}_{tg}\, dt$$

$$M_{tg} = M_{tg_i} + \int \dot{M}_{tg}\, dt$$

$$T_{tg} = T_{tg_i} + \int \dot{T}_{tg}\, dt$$

The parameters which generally experience the greatest change and therefore, have the greatest effect on the tank pressure are the gas mass and volume. The change in the mass of pressurizing gas is obtained from

the flowrates of any gases entering or leaving the tank, plus any mass transfer between liquid and gas phases in the tank. The change in gas volume is equal and opposite to the change in liquid volume in the tank. The change in liquid volume is primarily due to propellant outflow to the engines, but also includes the effects of propellant mass transfer and density changes.

The changes in tank gas temperature depend on the energy balance for the total tank gas. The energy terms involved in the balance are related to a number of possible factors:

1. Specific enthalpy and flow rate of the entering gas.
2. Mass transfer between gas and liquid phases.
3. Heat transfer between gas and liquid phases and between gas and tank wall.
4. Change in internal energy of the gas phase.
5. Expulsion work on the propellant

$$\dot{T}_{t_g} = \left[\frac{\sum \dot{Q}_g + \sum h_{g_e} \dot{m}_g + \sum h_{g_v} \dot{m}_{g_v} - \sum \dot{m}_g u_s - \frac{P_{t_s} \dot{V}_{t_g}}{J}}{\sum m_g C_v} \right]$$

where: $\dot{Q}$ = heat quantity rate

h = specific enthalpy of tank gas

$\dot{m}$ = mass flowrate of gas

u = specific internal energy

p = pressure of tank gas

$\dot{v}$ = rate of change for ullage volume

C_v = specific heat capacity at constant volume

Subscripts:

g = ullage gas

e = entering

v = vaporization

t = tank

The solutions to the equations for $\dot{m}_{t_s}$, $\dot{v}_{t_s}$, $\dot{M}_{t_s}$, and $\dot{T}_{t_s}$ require a knowledge of the thermodynamic properties of the gases concerned, the heat transfer rates, mass transfer rates, in-flow rate and temperature, and the out-flow rates.

Propellant Densities

Using the temperature and tank ullage pressure, the density of each propellant can be determined from the following expressions:

$$\rho_{ox} = f(P_{ox}, T_{ox})$$

$$\rho_{fuel} = f(P_{fuel}, T_{fuel})$$

Propellant Volume

The volume of propellants in the tanks is computed from the remaining weights and liquid density.

$$V_{fuel_t} = \frac{W_{fuel_t}}{\rho_{fuel}}$$

$$V_{ox_t} = \frac{W_{ox_t}}{\rho_{ox}}$$

Propellant Tank Volume

The total volume should be the volume of the tank under use conditions, i.e., tank stretch due to the internal pressure should be considered, and tank shrinkage due to the cryogenic propellants should be included.

$$V_T = V_c + \Delta V_p + \Delta V_{TEMP}$$

where:

V_T = Total tank volume under use conditions

V_c = Total tank volume at Opsig internal pressure and ambient temperature

ΔV_p = Change in total volume due to internal pressure

ΔV_{TEMP} = Change in total volume due to temperature

The tank ullage volume can be computed from:

$$V_{ULLAGE} = V_T - V_{PROP}$$

Acceleration Head

The vertical distance from the propellant levels in the tanks to particular levels of interest in the feed system is required (due to vehicle acceleration) in the calculation of pressures. The levels of interest in the simulation are the liquid levels, tank bottoms, engine feed system, interface, and thrust chamber. The heights from tank bottom to interface (HIT) and interface to thrust chamber (HCI) are considered, location dictated by TPS dimensions.

Tank Liquid Levels

The levels will be determined using height-volume tables. The volumes used will be the volume of all of the oxidizer or fuel left in the propulsion and feed system.

$$H_{fuel} = f(V_{fuel_t})$$

$$H_{ox} = f(V_{ox_t})$$

Total Height - Tank Liquid Level to Chamber

$$HCLFU = H_{fuel} + HIT + HCI$$

$$HCLOX = H_{ox} + HIT + HCI$$

Height - Interface to Injector Inlet

$$HLIFU = H_{fuel} + HIT$$

$$HLIOX = H_{ox} + HIT$$

Pressure at Bottom of Propellant Tank

$$P_{tb} = \frac{P_{tg} + (H_{prop})(\ddot{X}_{body} + G_{x_b})\rho_{prop}}{144g}$$

where:

P_{tb} = Pressure at bottom of propellant tank

P_{tg} = Ullage Pressure

H_{prop} = Height of Propellant in Tank

$\ddot{X}_{body}$ = Vehicle Acceleration along X body axis

G_{x_b} = Earth's gravitation along x body axis

ρ_{prop} = Density of propellant as a function of ullage pressure and temperature

g = Gravitational constant - 32.2 feet/second^2

Engine Equations

Propellant flow rates can be based on the Bernoulli equation:

$$\dot{W}_{prop} = \sqrt{\frac{144\rho(P_1 - P_2)}{R}}$$

where: P_1 = Inlet pressure - psi

P_2 = Outlet pressure - psi

ρ = Propellant Density - lbm/ft^3

R = Flow resistance - $lb_f\ sec^2/lb_m\ ft^5$

Flow Rate Relations

Mixture ratio = MR = $\dot{W}_{ox}/\dot{W}_{fuel}$

Total Propellant Flowrate = $\dot{W}_T = \dot{W}_{ox} + \dot{W}_{fuel}$

Engine Performance Equations

The engine performance equations for the SMS SSME simulation should be based on the digital simulation prepared by North American Rockwell Corp. This digital simulation for the SSME is described in NAR document RL00001, Rev. B. This approach should allow for the most convenient modification to the SSME simulation upon receipt of NAR change data and should provide for efficient correlation of simulator performance with NAR predicted, or actual performance, data for the SSME.

Controller Program - The Controller Program will be functionally simulated. A typical operational mission sequence is shown in Figure 4.3.2.1-5. This sequence is characterized by the successive occurrences of different engine operating phases. Each phase is characterized by the type of control functions which are occurring. These phases and characteristic functions are as follows:

(a) Checkout - Includes preflight calibration of pressure sensors and a simulated start and shutdown sequence, without propellants in the engine system.

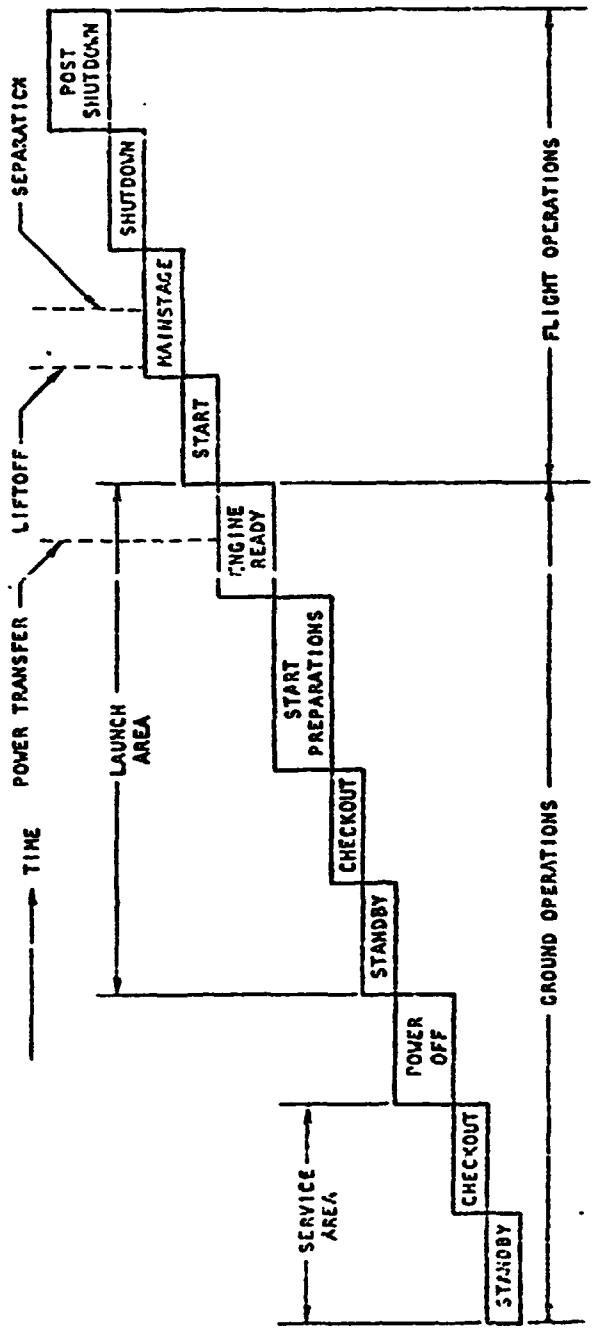


FIGURE 4.3.2.1-5

TYPICAL ENGINE MISSION SEQUENCE

F-398-8-A

(b) Start Preparation - Includes functions required to condition the engine for starting such as purging and control of propellant recirculation.

(c) Start - Functions required to start and sequence the engine to mainstage are included such as valve sequencing, ignition, and thrust buildup control.

(d) Mainstage - Encompasses functions required for continuous performance control in the mainstage power range which is between 50 percent and 109 percent of normal power level (NPL).

(e) Shutdown - Includes functions required to shutdown the engine such as thrust decrease ramp control, and programmed closing of valves.

(f) Post Shutdown - Normally a quiescent standby stage of control operation except for controller self test functions which occur continuously whenever power is one. Optional functions of propellant dumping or abort turnaround are possible during this phase.

During all phases of operation the Controller Program performs data processing functions for failure detection and status data supplied to the vehicle.

As system operation progresses through an operating phase, different combinations of control functions are operative at different times. These different operating combinations within a phases are defined as operating modes. As an example, the Mainstage phase has the following operating modes:

Normal Control

Thrust Limiting

Operating mode definitions for all phases are given in Table XIX. Operational program functions, their sequencing and timing will later be related to the phases and modes of system operation.

Because some functions are performed in more than one operating phase or mode the logic required for operational control of the functionally simulated SSME shall be divided into several groupings of functional logic which in combination are capable of performing all logical operations required for control of the SSME.

This specification presents a set of Functional Elements which define the requirements of the Controller Software. This has been done to more clearly present functional requirements of the program and to show the interrelation between these requirements. The Controller Program end product shall be made up of a set of subprograms called Computer Program Components (CPC's). Organization of the Operational Program into specific CPC's to coincide with the organization of the Functional Elements as presented in this specification is not a requirement. However, the resulting program must accomplish the functions and meet the performance requirements of this specification.

Controller Program Definition - The Controller Program shall satisfy the requirements of the nine Functional Elements shown in Figure 4.3.2.1.6. These Functional Elements are defined in the following subparagraphs.

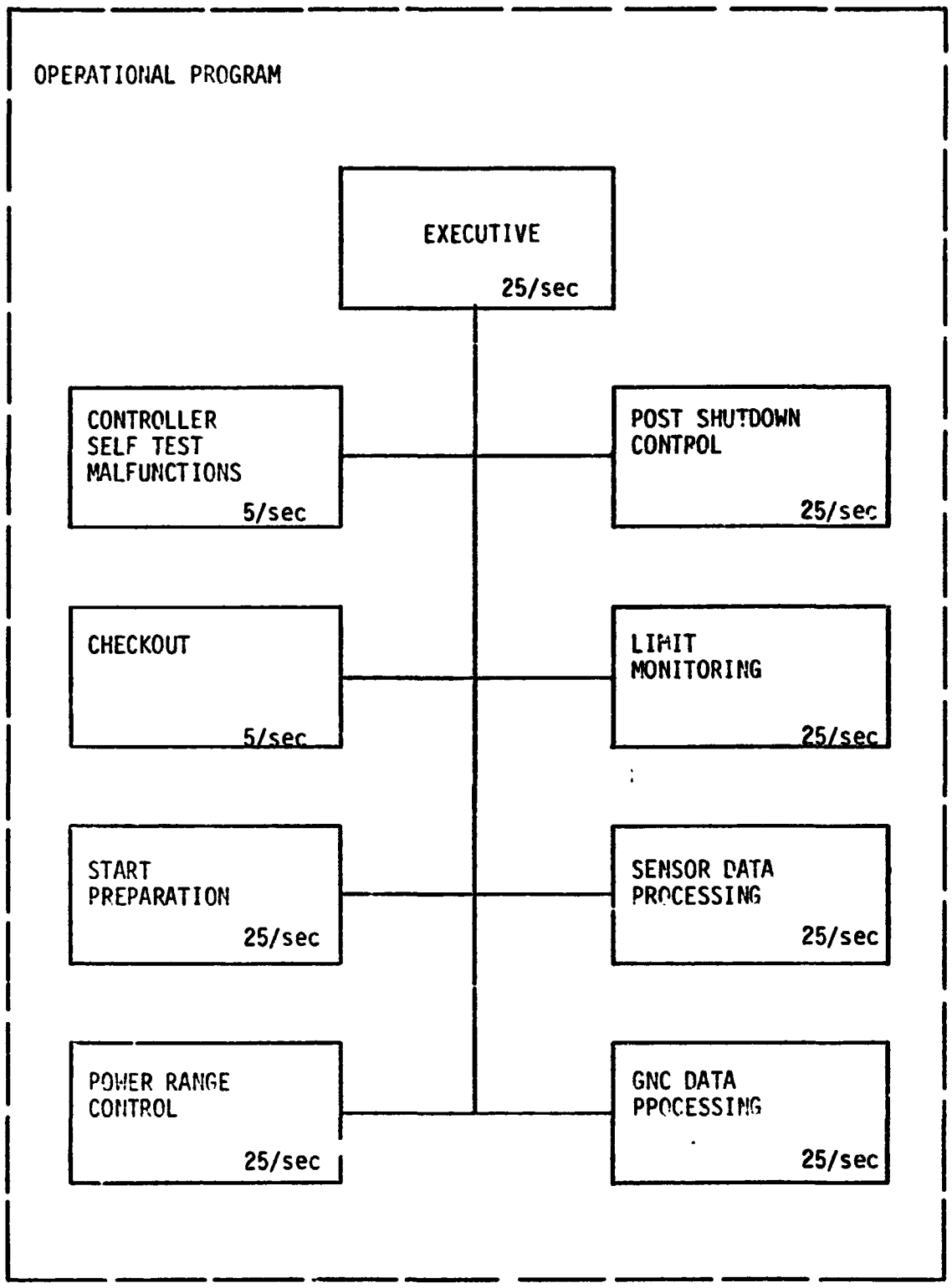


FIGURE 4.3.2.1-6

OPERATIONAL PROGRAM FUNCTIONAL ELEMENTS

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Executive Functional Element - This functional element establishes the sequence of operations to be performed by the controller software. Operation of the Executive Functional Element is cyclic. Under normal operation, whether on the ground for checkout or during flight, the controller computer progresses through the Executive Functional Element performing program logical operations in an endless loop (25/sec). Each loop through the functional element is called a major executive program cycle. The loop may be revised by any one of several types of events which cause an interrupt in the existing sequence:

(a) Command received from GNC alters a phase or mode of operation.

(b) A built-in test program determines component malfunction.

(c) Engine limit detection monitor determines an engine limit has been exceeded.

The Executive Functional Element contains the logic to evaluate all of the three events listed, update engine status information supplied to the GNC and change the combination of subprograms being processed by the computer.

Controller Self Test Functional Element - This functional element is executed once during every 5 major executive program cycles. It verifies the status of all controller components. If a component malfunction which does not impair the operability of the controller is detected, the malfunction is indicated and the next step normally performed in the test sequence is executed. If a malfunction occurs which results in an inoperative controller channel, the malfunction is indicated and control is transferred to the Executive Functional Element for the processing of channel shutdown.

Checkout Functional Element - This functional element performs preflight calibration of specified performance control sensors. A simulated start and shutdown sequence is also provided to verify the operation of some sensors, engine control components, without propellants in the engine system.

Start Preparation Functional Element - This functional elemert controls system purges and propellant conditioning during preparation for engine start. It also verifies propellant conditions prior to indicating an Engine Ready status for start.

Four sequence conditions are required to condition the engine for start. These include: (1) GN2 (gaseous nitrogen) purge of oxidizer system and HPOT (high pressure oxidizer turbopump) Turbine Seal until engine start and helium purge of HPOT Intermediate Seal; (2) helium purge of the fuel system prior to dropping propellants; (3) propellant recirculation when propellants are dropped; and (4) helium purge of the fuel system repeated prior to engine start. The time allocated for each purge is controlled by the vehicle. Interlocks in the software program verify that the sequence is correct and that conditions are acceptable prior to initiating each purge. Correct purge pressure conditions are verified each major cycle of the Executive Functional Element.

Power Range Control Functional Element - This functional element controls engine operation during the start, mainstage, and shutdown phases of engine operation.

During start, valve positions are sequenced and programmed, igniters are energized, ignition verified, and closed loop thrust and mixture ratio control is initiated.

In the Mainstate Phase, engine thrust and mixture ratio are controlled to reference levels supplied from the GNC. The thrust and mixture ratio control perform dynamic compensation functions on feedback sensor signals, conditioning of reference signals for rate of change and limits, computation of performance errors and control compensation of derived errors to provide control valve position reference signals. Closed loop temperature limit control functions are also performed.

Thrust decrease programming and valve sequencing functions are performed during the Shutdown Phase. Logic is also provided for Limit Shutdown or Emergency Shutdown from any thrust level.

Post Shutdown Control Functional Element - This functional element contains control logic for the engine during the Post Shutdown phase of engine operation. Three types of operational modes are controlled by the logic and may be selected by vehicle command. These are:

(a) Standby

(b) Propellant Dump (Oxidizer Dump and Fuel Dump Modes)

(c) Abort Turnaround (Sequence No. 1 & Sequence No. 2 Modes)

Standby - This is a waiting mode of controller operation normally entered at the completion of the Shutdown phase. In this mode only the Executive, Sensor Data Processing, GNC Data Processing, and Controller Self-test Functional Element operations are being performed.

Propellant Dump - The propellant dump modes of operation sequences valves and provides interlocks for safe control of propellant dumping. The duration of dumping for each propellant is controlled by the GNC. Separate commands are required from the GNC to initiate oxidizer dumping, then fuel dumping, and terminate the process.

Abort Turnaround - The abort turnaround modes of control are a modified Start Preparation sequence used to prepare the engine for start shortly after an aborted firing. The sequence timing is controlled by the GNC. Logic is provided to ensure that a proper sequence is performed and that conditions are correct before an Engine Ready Status signal is given.

Limit Monitoring Functional Element - This functional element checks limit shutdown parameters and actuator position errors against specified limits relative to the phase operating requirements. Unsatisfactory status conditions are identified for evaluation and corrective action.

The Limit Monitoring Functional Element is operative every major executive program cycle. During all operational phases propellant valve position commands and indicated positions are compared to verify correct positioning. Monitoring functions for other system parameters occur during flight operation. These functions vary according to the operating phase and status within the phase.

Sensor Data Processing Functional Element - This functional element is active every executive program cycle. It scales raw data from sensors with redundant channels. Scaled values are obtained by using calibration constants stored in memory. Status on malfunctioned sensors is indicated. This functional element also processes scaled sensor measurements to produce propellant weight flow rates, engine mixture ratio, and thrust level data for control and engine maintenance recording.

Vehicle Data Processing Functional Element - This functional element is operative during all phases. It processes engine status, performance and maintenance trend data to the proper format required for transmission to the vehicle.

Program Interface - As shown in Figure 4.3.2.1-7 data flow to the Controller Functional Program comes from GNC commands, controller elements and engine system sensors through the GNC/Engine and Controller/Engine Interface. The Controller Program produces status information and performance data which is transmitted to the GNC through the GNC/Engine Interface. The Controller Program also produces control command signals which control engine functions through the Engine/Controller Interface.

GNC/Engine Data Interface - The Controller Program provides for accepting and responding to GNC commands. The format of GNC commands transmitted via the GNC/Engine Command channels to the controller shall be as defined in Table IV. The format of data transmitted from the controller via the GNC/Engine Recorder channels every data transmission cycle (every 40 ms) shall be as defined in Table VI. Data transmitted from the controller via the GNC/Engine Command channels in response to a Status Request command shall be as defined in Table V.

Controller - Engine Data Interface - The Operational Program provides for accepting engine sensor data and producing control signals. See Tables IX, I and II for sensor ranges, temperatures limit control range and engine limit control shutdown parameter.

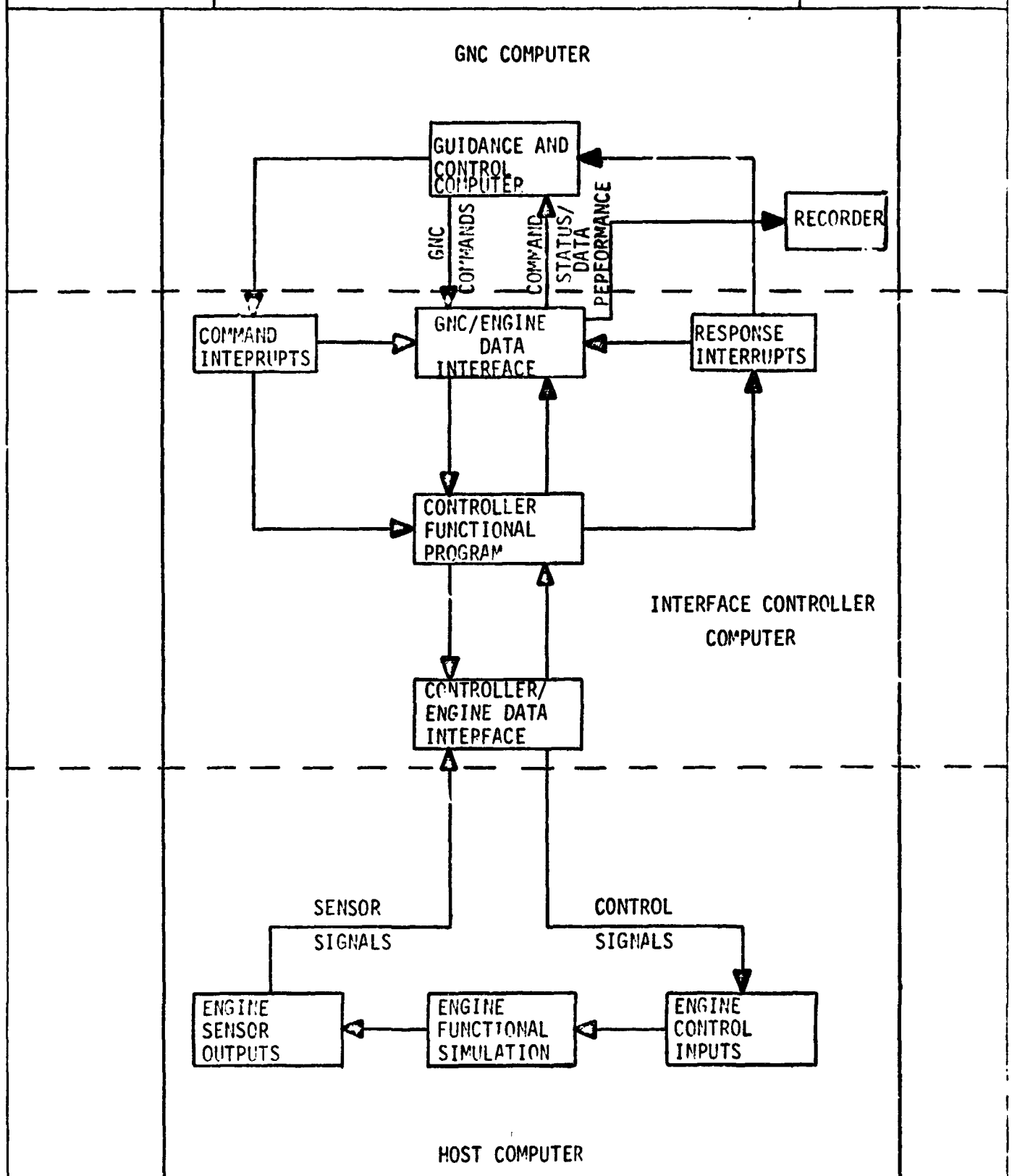

FIGURE 4.3.2.1-7

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Performance of Controller Software

Executive Functional Element - The Executive Functional Element shall control Controller Program sequencing and perform logical operations so that the following operational requirements are satisfied.

Engine Status - Engine status information, defined in Table V, shall be computed and updated every major executive program cycle (25/sec). This information shall be available for transmission to GNC upon receipt of a Status Request command. This required status information, supplemented as necessary by additional status information computed solely for program use, shall be used in conjunction with logic to validate (accept or reject) GNC commands and establish sequencing and interlocking of controller functions.

GNC Command Processing - The Executive Functional Element shall receive commands in the format defined by Table VII from all operable GNC/Engine Command channels. Any single command channel shall be disqualified from GNC command processing by any one fo the following commands from GNC: Command Channel 1 Inhibit, Command Channel 2 Inhibit or Command Channel 3 Inhibit. The inhibit to any command channel shall be removed by any one fo the following commands from GNC: Command Channel 1 Enable, Command Channel 2 Enable or Command Channel 3 Enable. Command words from GNC, to disquality and restore command channels, shall be via the remaining operational command channels.

GNC commands shall be of two types: absolute commands and variable commands. The variable commands are Thrust Level and Mixture Ratio. All other commands are absolute commands.

GNC Command Validation - Commands from the GNC shall be validated or rejected by command channel voting and agreement with engine operating phase.

Command Channel Voting - Absolute commands shall agree exactly in content for all operable command channels. Variable commands shall agree within (TBD) percent of each other if all three command channels are operative, and (TBD) percent if only two channels are operative. For operation with three good channels, two out of three agreement constitute a good vote. For two good channels, both channels must agree in order to constitute a good vote. Failure to obtain a good vote shall result in a Message Reject Code to be transmitted to the vehicle.

Command Agreement with Phase - After a command has been validated by command channel voting, the command shall be checked for agreement with engine phase of operation in accordance with Table IV and the requirements (a) through (f) below. If a command is determined to be invalid due to disagreement with engine phase or mode of operation, a Message Reject code shall be transmitted to the GNC.

(a) Checkout Phase - This phase of operation may be entered upon initial power on, or from the Start Preparation or Post Shutdown phases subsequent to the receipt of a Controller Reset Command. There shall be no restrictions on switching between functional modes of this phase.

(b) Start Preparation Phase -- This phase shall be entered only if checkout is complete. GNC start preparation phase commands received during this phase shall not be implemented if they are not in normal sequence or within the time limits specified in "Start Preparation Functional

Element". The Start Preparation phase sequence may be started over provided criteria for start of the phase are still satisifed.

(c) Start Phase - This phase shall be entered only if Engine Ready status conditions are satisifed and all Start Preparation or Abort Turnaround procedures have been completed. GNC Limit Control Inhibit commands shall be ignored until ignition has been confirmed.

(d) Mainstage Phase - This phase is entered from the Start phase without a GNC command.

(e) Shutdown Phase - Once initiated it shall not be possible to initiate a new phase until all functions of this phase have been completed. Only the Post Shutdown phase may be entered after the Shutdown Phase.

(f) Post Shutdown Phase - This phase shall be entered only after the Shutdown phase.

Implementation of Vehicle Commands - All commands from the vehicle, except the Status Request command, shall be implemented after a Command Execute command has been received and validated. A validated command shall not be implemented if a command other than Command Execute is subsequently received.

Command Failure Identification - When a Message Reject code is the result of GNC command processing, then the failure identification code for Invalid GNC command shall be inserted in the failure identification word and the failed parameter word shall contain the rejected command code.

When a failure which can be isolated to an individual command channel is detected by command channel voting, then the failure identification code for one of the GNC/Engine Command Channels shall be inserted in the failure identification word. The test number word shall contain the number of times a fault has been isolated to that channel and the failed parameter word shall contain the command as received on that channel. When a failure has been verified for three successive commands from the GNC on any single command channel, then that channel shall be disqualified from future GNC command processing until a Command Channel Enable command is implemented for that channel.

Malfunctions - The Executive Functional Element shall receive and respond to failure status indications in accordance with Table XII.

Cycle Time - The Executive Functional Element shall complete a computational cycle at least every 40 milliseconds.

Response to Interrupts - The Executive Functional Element shall include the capability to respond to program interrupts caused by but not limited to:

(a) Controller Failure

(b) Servovalve Redundancy Failure

(c) Vehicle Command

Controller Self Test Functional Element - This functional element shall verify the status of all controller components except components which are checked as part of the sensor input tests of the Sensor Data Processing, and Checkout Functional Elements. Self test shall be performed every five major executive program cycles. All malfunctions will be monitored in this program.

Checkout Functional Element - This functional element shall perform Preflight Calibration, a simulated start and shutdown sequence and other operations associated with the Checkout phase of engine operation.

Checkout Conditions - Upon receipt of a Controller Reset command the Operational Program shall be initialized as follows:

(a) The Engine Status Word shall be set to the Standby mode of Checkout and to indicate Engine OK.

(b) All failure indications shall be reset to indicate no failures.

(c) All propellant valves shall be commanded closed.

(d) All solenoid and torque motor coils shall be de-energized.

(e) All disqualified component channels shall be restored to normal operation.

(f) All I responses as defined by Table XII and their overrides shall be reset.

(g) Checkout Complete and Engine Ready Status shall be negated.

Verification of No Propellant Drop and Hydraulic System Pressure, and Flowmeter Spin Limit Control shall be performed every major executive program cycle during the Checkout phase. Executive, Controller Self-Test, Sensor Data Processing and Vehicle Data Processing operations applicable to the Checkout mode shall be continuously active during this phase. The actuator fail-safe coils and the Emergency Shutdown Control Valve Coil shall be de-energized during Checkout, except where energization of these coils are

necessary to perform checkout requiring hydraulic actuation of the propellant valves or to checkout the Emergency Shutdown control system.

Start Preparation Functional Element - This functional element shall control system purges and propellant conditioning during preparation for engine start. It shall also verify that satisfactory conditions exist for Start prior to updating of the Engine Status Word to Engine Ready. Propellant valves shall remain closed, igniters shall remain off and the measured hydraulic pressure shall remain within tolerance.

The initiation and duration of each purge is controlled by GNC command. A specified set of operations shall be performed upon the receipt of each purge command from the GNC. Functions performed in response to each GNC command are defined and given in their normal sequence in the following subparagraphs.

Purge Sequence No. 1 (Oxidizer System High Pressure Oxidizer Turbo-Pump (HPOT) Turbine Seal and Intermediate Seal Purges - The operations associated with this sequence are initiated after validation of a Purge Sequence No. 1 command from the GNC. Operations of this sequence are defined in Table XIII Part A.

Purge Sequence No. 2 (Fuel System Purge) - GNC commands for initiation of this sequence shall not be accepted unless the operations of sequence No. 1 have been accomplished and at least 4 minutes have elapsed since the initiation of sequence No. 1. After receipt and validation of a Purge Sequence No. 2 command from the GNC the operations of Table XIII Part B shall be performed.

Purge Sequence No. 3 (Propellant Recirculation) - GNC commands for initiation of this sequence shall not be accepted unless the operations of Sequence No. 2 have been accomplished and at least 3 minutes have elapsed since the initiation of Sequence No. 2. After receipt and validation of a Purge Sequence No. 3 command from the GNC the operations of Table XIII Part C shall be performed.

Purge Sequence No. 4 (Fuel System Purge After Propellant Drop) - Commands for this sequence shall not be accepted until 27 minutes have elapsed from the initiation of Purge Sequence No. 3. After validation of a Purge Sequence No. 4 command from the GNC the operations of Table XIII Part D shall be performed.

Engine Ready Conditions - An Engine Ready status signal shall be provided to the GNC at the completion of engine conditioning for start if conditions are correct. The following conditions must exist for an Engine Ready status signal to be provided to the GNC.

(a) All propellant valves must be closed.

(b) Hydraulic system pressure must be within the same tolerance band as required during checkout.

(c) Propellant inlet conditions verified per Table XIV as correct continuously for previous three minutes.

(d) Controller self test condition satisfactory.

(e) Thrust Level and Mixture Ratio commands have been received.

(f) There are no I responses as defined in Table XII in effect.

The Engine Ready status shall be negated (Engine Status Word set to Purge Sequence No. 4) if system conditions cease to satisfy Engine Ready requirements any time prior to Start command.

Power Range Control Functional Element - This functional element contains the sequential and performance control logic necessary for operation of the Space Shuttle Main Engine during the Start, Mainstage, and Shutdown Phases of operation.

Start Sequencing - Start Sequencing shall be initiated upon receipt and validation of a Start command from GNC. Initiation of this sequence coincides with the beginning of the Start Phase of engine operation. Operations performed as part of the start sequence are defined in Table XV.

Shutdown Sequencing - Shutdown sequencing shall be initiated upon receipt and validation of a Shutdown command from the GNC or upon controller derived limit shutdown commands. Program logic shall provide for engine shutdown from any power level.

Normal Shutdown - A shutdown is normal if initiated by a Shutdown command from the GNC when engine thrust is between Minimum Power Level (MPL) and Emergency Power Level (EPL), the thrust and mixture ratio control loops are active, and no engine failure conditions exist which could interfere with the sequence. The sequence for such a normal shutdown shall be as defined in Table XVI.

Limit Shutdown - Limit Shutdown of the engine shall be initiated when hydraulic actuation controls are functional for the propellant valves and an Engine Limit Exceeded indication via the Engine Status Word is received from the Limit Monitoring Functional Element as described in "Limit Shutdown Monitoring". Specific cases where Limit Shutdown conditions exist

are indicated by the S responses in Table XII. During Start after ignition has been confirmed (see Table XV) and during Mainstage, the Limit Control Enable command must be in effect before Limit Shutdown is initiated. If the Limit Control Inhibit command is in effect for these phases, the Limit Shutdown Logic shall not cause an engine shutdown.

If the thrust reference is greater than MPL, then the Limit Shutdown sequence shall be initiated at the beginning of Part A of Table XVI. If the thrust reference is less than or equal to MPL then the Limit Shutdown sequence shall be initiated at the beginning of Part B of Table XVI.

Emergency Pneumatic Shutdown - Emergency Pneumatic Shutdown shall be initiated when any one of the following conditions is verified three successive times for each measurement channel.

(a) Failure of hydraulic actuation controls to any propellant valve as indicated by the failure of both actuator channels.

(b) Failure of two or more channels of a triple redundant sensor.

(c) Electrical power has been lost and then recovered after a 50 (plus 20, minus 0) millisecond period and all propellant valves have not reached closed at the time of power recovery.

Pneumatic Shutdown will also be the result of power loss to solenoid and torque motor coils when both channels of the controller or 400 Hz Power Bus fail. Specific cases where Pneumatic Shutdown conditions exist are indicated by PS responses in Table XII.

Pneumatic Shutdown shall be initiated by de-energizing the fail-safe coils of all actuators and the Emergency Shutdown Control Valve Coil. The Engine Status Word shall be changed to indicate the Fail-Safe Pneumatic mode of the Shutdown phase and to indicate Component Failed.

When all propellant valves reach the closed position, the shutdown sequence then continues at the beginning of Part C of Table XVI.

When both Limit Shutdown and Pneumatic Shutdown conditions exist concurrently, Pneumatic Shutdown shall have precedence. The Limit Control Inhibit command shall not prevent Pneumatic Shutdown of the engine.

Performance Control Requirements - The Power Range Control Functional Element shall contain the control logic necessary for the Space Shuttle Main Engine system to satisfy the performance control criteria set forth in RC1007.

Temperature Limit Control - The High Pressure Oxidizer Turbopump (HPOT) and High Pressure Fuel Turbopump (HPFT) Turbine Discharge Temperatures shall be monitored for Temperature Limit Control in accordance with RC1007 and the requirements stated herewith. The Temperature Limit Control shall be enabled when (a) the engine is in the Start or Mainstage phase of operation, (b) the Limit Control Enable command has been received from the vehicle and is in effect and (c) ignition has been confirmed. The Engine Status Word shall be changed to indicate the Thrust Limiting mode when the Temperature Limit Control has been enabled and one of the following conditions exists:

(a) Both measurements channels of a Temperature Limit control sensor indicate operation outside the limits and conditions specified in Table I.

(b) Thrust is otherwise being limited by the Temperature Limit Control.

If both measurement channels of a Temperature Limit Control sensor have passed reasonableness tests but failed the comparison tests, the lower indicated temperature shall be used for Temperature Limit Control. The Temperature Limit Control shall be deactivated upon initiation of the Shutdown phase, or when the Limit Control Inhibit command is in effect.

Chamber Coolant Valve Position Scheduling - The CCV position shall be scheduled as a function of engine thrust reference when the thrust reference is at or above the MPL level. Valve actuator position shall be scheduled linearly with thrust reference so as to be 30 percent open at MPL and full open at NPL. The CCV shall be full open at thrust reference levels above MPL.

Main Oxidizer Valve Position Scheduling - The MOV position shall be scheduled as a function of computed engine thrust after MPL has first been attained at engine start. Valve actuator position shall be scheduled linearly with thrust so as to be full open at NPL and (TBD) percent open at MPL. The MOV shall be full open at thrust levels above NPL.

Main Fuel Valve Position Scheduling - The MFV position shall be scheduled as a function of computed engine thrust after NPL has first been attained at engine start. Valve actuator position shall be scheduled linearly with thrust so as to be full open at NPL and 62 percent open at MPL. The MFV shall be full open at thrust levels above NPL.

Post-Shutdown Control Functional Element - This functional element contains the logic for engine control during the Post Shutdown phase of engine operation. Executive, Controller Self-Test, Sensor Data Processing and GNC Data Processing Functional Element operations applicable to Post Shutdown shall be continuously active during this phase. Requirement for each of the three modes of operation are defined in the following subparagraphs. The Emergency Shutdown Control Valve shall remain de-energized during all modes of Post Shutdown except for the Abort Turnaround modes.

Standby - The Post Shutdown Functional Element shall automatically begin operation in this mode. This mode of oepration is the normal status for control operation at the completion of shutdown.

Propellant Dump - This mode of Post Shutdown operation shall be initiated upon vehicle command if the preceding shutdown was not caused by a failure of the MFV or MOV actuator. The sequence is always initiated from the Standby Mode of the Post Shutdown Phase. Vehicle commands required for this mode of operation and the sequence in which they are normally received are: Oxidizer Dump, Fuel Dump, and Terminate Propellant Dump. This sequence may be modified by a Terminate Propellant Dump command used to terminate an oxidizer dump.

Oxidizer is always dumped before fuel, only one main valve may be open at any time, and a fuel dump must always be preceded by a 10 second fuel system purge. The sequence and timing for this mode is defined in Table XVII. Part A of the sequence, oxidizer dumping, is initiated by receipt of an Oxidizer Dump command. Part B of the sequence, fuel dumping, is initiated by a Fuel Dump command which also terminated Part A of the sequence. Part C of the sequence, propellant dump termination, is initiated by a Terminate Propellant Dump command which shall terminate oxidizer dump or duel dump at any point in the sequence.

Abort Turnaround - This mode of Post Shutdown operation shall control system purges and propellant conditioning during preparation for engine start after an abort. It shall be initiated upon vehicle command if the preceding shutdown was not caused by an engine malfunction. The sequence must always be initiated from the Standby Mode of the Post Shutdown Phase. Venicle commands required for this mode of operation and the sequence in which they must be received are Abort Turnaround Sequence No. 1 and Abort Turnaround Sequence No. 2.

Abort Turnaround Sequence No. 1 (Initiation of Gaseous Nitrogen (GN2), Fuel System, and Intermediate Seal Purges) - The operations associated with this sequence are intiated after validation of an Abort Turnaround Sequence No. 1 command from the GNC. The sequence continues until a new valid command is received from the vehicle. Operations of this sequence are defined in Table XVIII, Part A.

Abort Turnaround Sequence No. 2 (Propellant Recirculation) - Vehicle commands for initiation of this sequence shall not be accepted unless the operations of Sequence No. 1 have been accomplished and at least 2 minutes have elapsed since initiation of Sequence No. 1. After receipt and validation of an Abort Turnaround Sequence No. 2 Command from the vehicle, the operations of Table XVIII, Part B shall be performed.

Limit Monitoring Functional Element - This functional element shall check engine limit shutdown parameters and actuator position errors for their values relative to specified limits which are a function of the operating information shall be updated and either switching to continued operation on a redundant channel, or engine shutdown intiated in accordance with "Malfunction Response".

Actuator Position Error Monitoring - This function shall be performed during all phases of engine operation. The computer produced position reference signal for each actuator channel shall be compared with its corresponding actuator channel position indication to obtain an indicated position error. If excessive position error is confirmed with three successive samples, the controller shall respond in accordance with the corrective action specified for servovalve channel failure. If the servo positioned actuator has been commanded and reached full open or closed, then a position error greater than 2 percent on both channels shall cause swtiching.

Limit Shutdown Monitoring - Engine parameters shall be monitored to determine conditions for Limit Shutdown in accordance with RC1007 and the following subparagraphs. For conditions which cause Pneumatic Shutdown refer to "Emergency Pneumatic Shutdown".

Start Transient Parameter Monitoring - The Main Combustion Chamber Pressure shall be monitored during Start, after ignition has been confirmed, to verify that the pressure remains within the specified limits as a function of time. Three successive out of limit pressure indications shall cause Engine Limit Exceeded to be indicated by the Engine Status Word, the failure identification word to be set to 121 and Limit Shutdown initiated in accordance with "Limit Shutdown".

Limit Shutdown Parameter Monitoring - Engine limit Exceeded shall be indicated by the Engine Status Word and Limit Shutdown initiated in accordance with "Limit Shutdown" if either of the following conditions have been verified three successive times for each measurement channel.

(a) When all measurement channels, which have passed sensor reasonableness tests, for an engine limit parameter indicate operation outside the engine limits and conditions imposed by Table II, the failure identification word shall be set to indicate one of the "out of limits" failure modes.

(b) When both measurement channels of a dual redundant sensor used for Engine Limit Shutdown Control fail to pass reasonableness tests, the failure identification word shall be set to indicate that one of the sensor channels has failed.

Sensor Data Processing Functional Element - This functional element contains the logic for sensor data scaling, tests, and performance parameter calcualtions.

Types of Sensor Data Processing - Sensor data processing shall depend upon the application of the measured data.

Data Scaling - Raw data from all sensors shall be scaled to accommodate sensor calibration curve characteristics and obtain measured parameter values for use in controller calcualtions and maintenance recording. The coefficients of these equations shall be data constants in the program which can be changed when sensors are replaced in the engine system. Raw data from non-redundant sensors shall not be scaled.

Sensor Data Reasonableness Tests - After data scaling, reasonableness tests shall be performed on data from specified sensors. Data from sensors failing this test shall not be used in controller performance calcualtions. If a measurement fails the reasonableness test three successive times it shall be continuously rejected until a Controller Reset command is received and implemented.

Comparison Tests - Comparison tests shall be performed on specified dual and triple redundant measurements. If one measurement channel of a triple redundant sensor fails the comparison tests three successive times, that channel shall be continuously rejected until a Controller Reset command is received and implemented.

GNC Data Processing Functional Element - This functional element shall process engine status, performance and maintenance trend data to the proper format required for transmission to the GNC/Engine Interface. Data and command word format are defined in Table VII.

Data Base - Parameter measurements, sensor ranges, units of measure which shall be accommodated by the Controller Program are defined in MC1007 and Tables IX, I, and VI.

4.3.2.2 Reaction Control Subsystem

The Reaction Control Subsystem can be simulated by dividing the system into four basic areas of equations. Figure 4.3.2.2 shows the four equation groups and the general interface requirements. Because of the fast response rate of the real world system, the simulation is approached for thrust from the equivalent engineering parameter of total impulse. The helium pressurization equations are to be a combination of exact engineering relationships and functional representation.

The helium pressurization equations will use the EPS power available booleans and the crew station switch and circuit breaker state to derive the valve state. Primary helium storage tank pressure and mass is calculated from helium usage. Helium usage is based on RCS fuel remaining in the tank. Helium pressure on the bladder hydrazine tank is calculated as dependent on the helium regulation supply.

The hydrazine fuel equations provide the calculations for the fuel remaining in the tank. Fuel usage will be calculated by the thrust equations. A fuel available and pressurized boolean will be generated for the thrust equations.

The thrust and force equations will calculate the total impulse of the RCS jets as they fire. An interface program with the G, N and C computer will provide the thrust equations with booleans for firing the jets and a length of time fired parameter. These conditions, along with electrical power for the catalytic heater through switches and circuit breakers, will be used to computer the total impulse of each jet since the last computer cycle through this program. The electrical load for the catalytic heater will be calculated for the EPS program and the total impulse will be generated for the EOM program. The computed impulse will take into account the loss of efficiency as the result of atmospheric pressure.

The instrumentation and signal conditioning equations will accept parameters simulating the actual system state and condition these parameters using sensor and display logic booleans from the Electrical Power Subsystem for crew station display, for input to the Caution and Warning Subsystem, or for input to the Telemetry Subsystem Multiplexer Program. The equations will be repeated for each reaction control system unit, either by programmed loops or by repetitive equations whichever requires the least amount of computer time and core. Required malfunctions for the RCS simulation are to be designed into the simulation for minimum computer impact.

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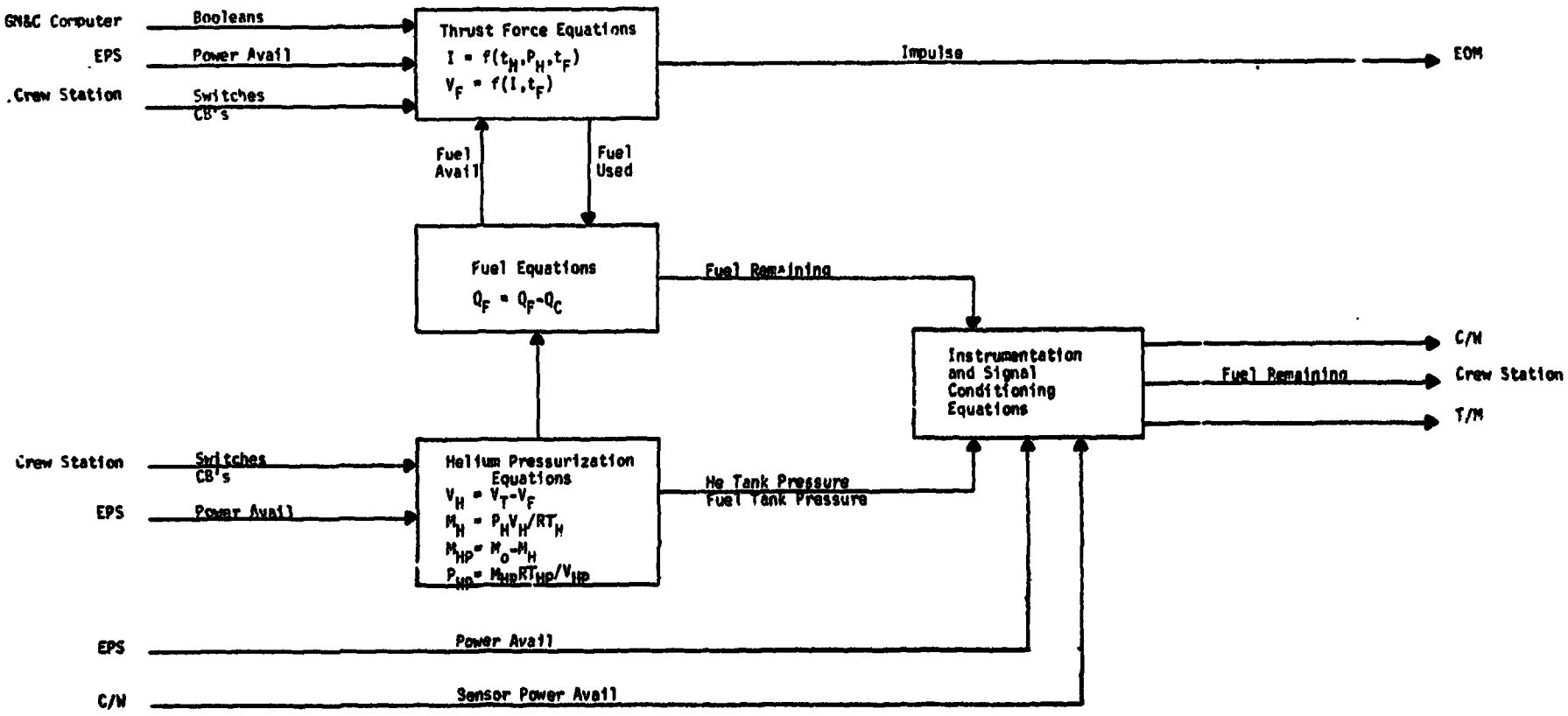
4.3.2.2 Reaction Control Subsystem



where: V_H = Volume of Helium

V_T = Volume of fuel tank

V_F = Volume of fuel

M_H = Mass of helium

P_H = Pressure of helium

T_H = Temperature of helium

R = Universal gas constant

M_{HP} = Mass of helium in high pressure tank

M_o = Original mass of helium in high pressure tank

P_{HP} = Pressure of helium in high pressure tank

T_{HP} = Temperature of helium in high pressure tank

V_{HP} = Volume of helium in high pressure tank

Q_F = Quantity of fuel

Q_C = Quantity of fuel consumed

I = Impulse force of engine

t_F = Firing duration per iteration

t_H = Temperature of reaction plate

4.3.2.3 Orbital Maneuvering Subsystem

The simulation of the Orbital Maneuvering Subsystem may be approached by a combination of logical equations, functional representative equations, and explicit engineering equations. Crew displays are provided for fuel, oxidizer, helium, and engine chamber pressure, and for oxidizer and fuel quantity. Refer to Figure 4.3.2.3.

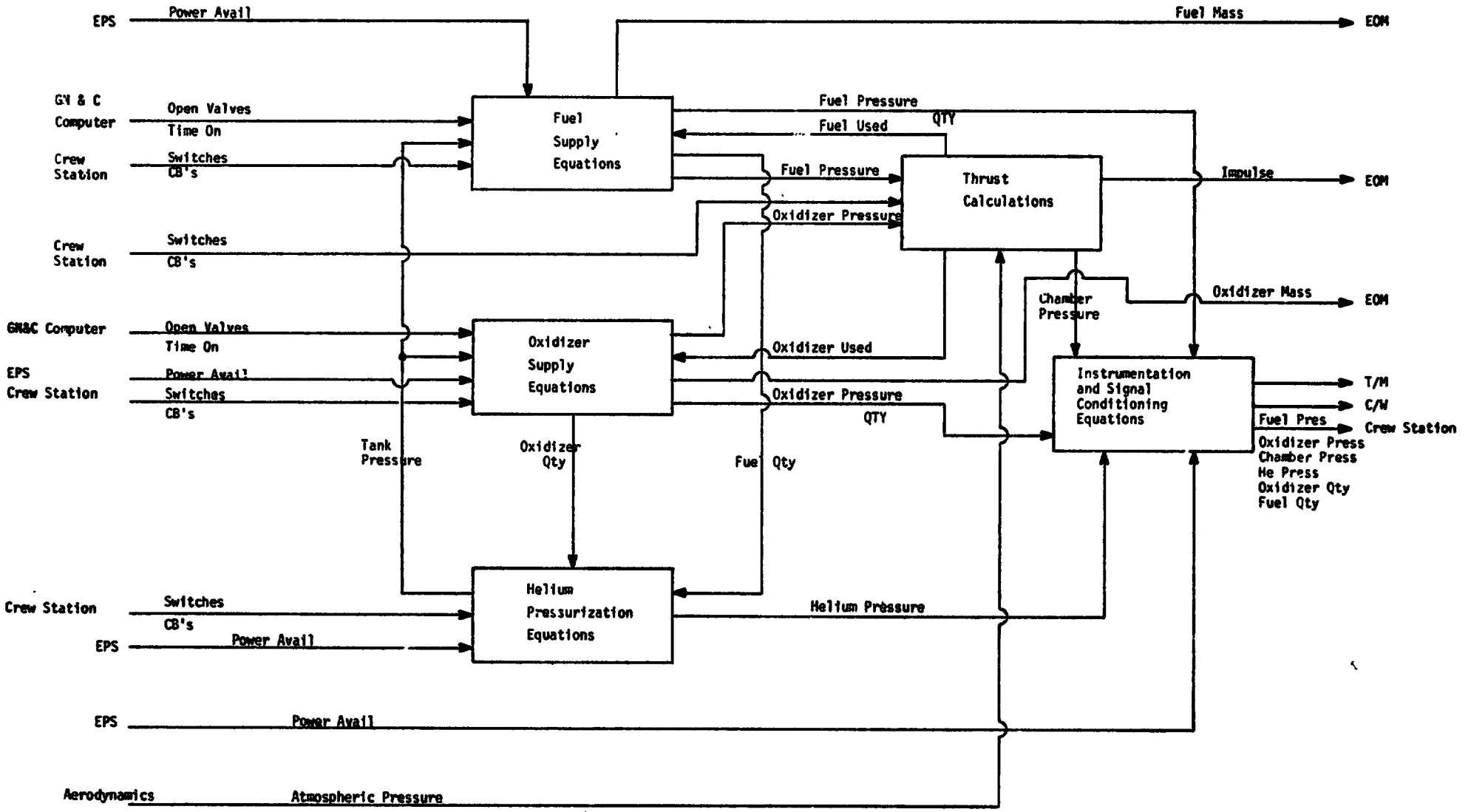
The helium pressurization equations will use the EPS power available booleans and the crew station switch and circuit breaker state to derive the valve state of the helium system. Primary helium storage tank pressure and mass is calculated from helium usage. Helium usage is based on the amount of propellants left in the oxidizer and fuel tanks. Helium pressure on the fuel and oxidizer is calculated as dependent on the helium regulation supply.

The fuel supply equations provide the calculations for the fuel quantity remaining in the tank. Fuel usage will be calculated by the thrust equations. A fuel available and pressurized boolean will be generated for the thrust equations.

The oxidizer supply equations perform the same basic function as the fuel equations - calculation of oxidizer quantity, oxidizer available and pressurized. Oxidizer usage will be calculated by the thrust equations.

The thrust calculations are to compute the impulse of the engines during the time period from the last iteration to the present iteration. This particular method will allow simulation of the correct impulse during both start-up and engine shut-down transients. The impulse from the engine will reflect the fuel and oxidizer pressure and the mixture ratio corrected by atmospheric pressure.

Figure 4.3.2.3 - Orbital Maneuvering System



Chamber pressure will be calculated for display purposes from the computed impulse force.

The instrumentation and signal conditioning equations will accept parameters simulating the actual system state and condition these parameters using sensor and display logic booleans from the Electrical Power Subsystem for crew station display, for input to the Caution and Warning Subsystem, or for input to the Telemetry Subsystem Multiplexer Program. The equations will be repeated for each Orbital Maneuvering system unit, either by programmed loops or by repetitive equations, whichever requires the least amount of computer time and core. Required malfunctions for the OMS simulation are to be designed into the simulation for minimum computer impact.

4.3.2.4 Air Breathing Engine System

The Air Breathing Engines of the shuttle vehicle are to be simulated using a closed-loop dynamic functional math model. The fundamental overview of the engine shows fuel management, crew displays, throttle control, and thrust as the primary system functions.

The throttle is the primary input to the fuel control system. In addition the fuel flow responds to the high pressure compressor rotor speed and discharge pressure, the low pressure compressor inlet air temperature and pressure, and the internal burner pressure.

The engine inlet air temperature is a function of the ambient air temperature and the ram air effects from aircraft speed. The inlet pressure is also dependent on ambient air pressures and the ram air effects.

The airflow of the compressors is a function of the inlet conditions as well as the rotor speed and ducting losses.

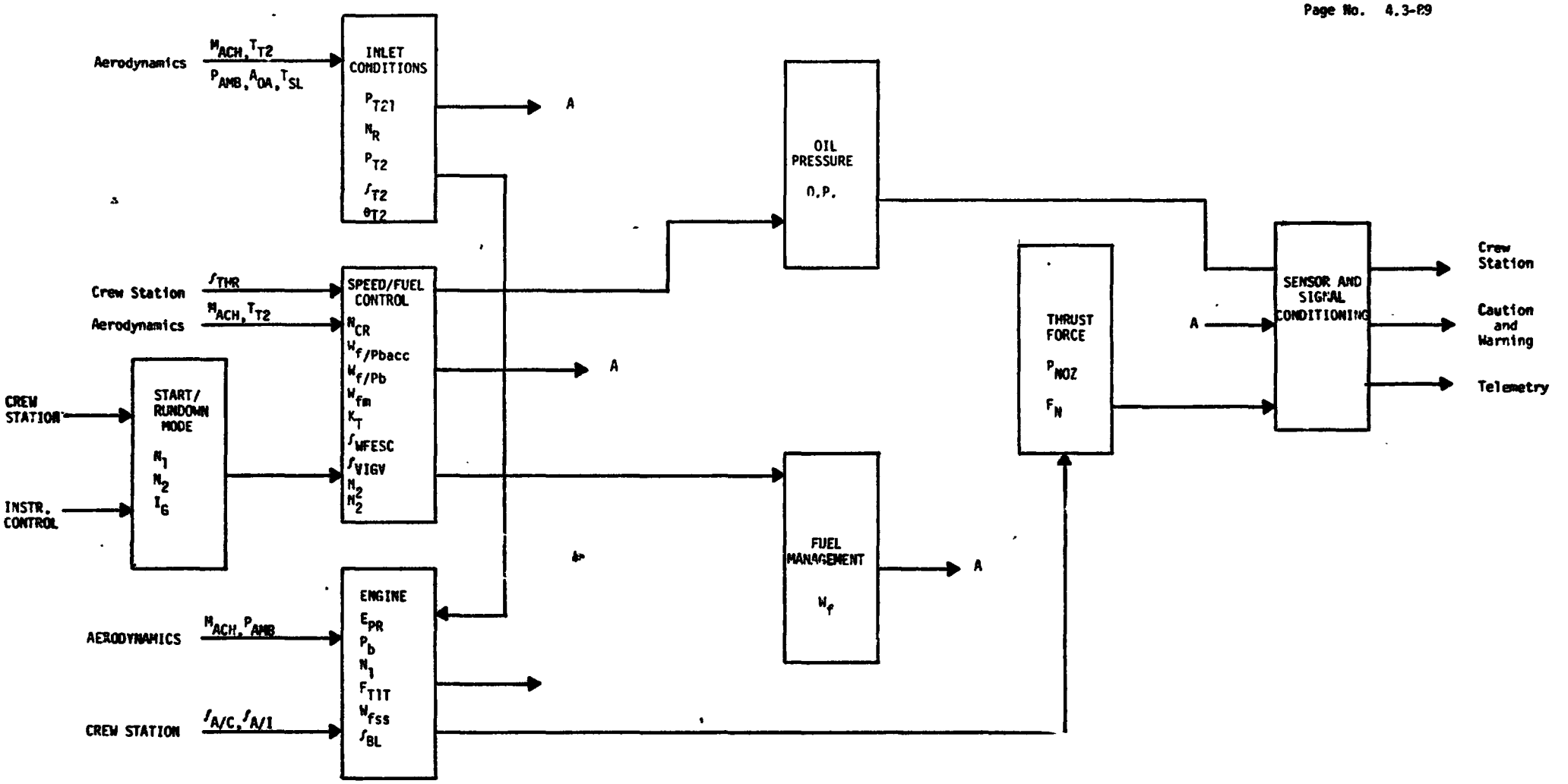
The burner outlet pressure and temperature are functions of the high pressure compressor outlet pressure, fuel flow, airflow through the compressor, and air bleed losses. The turbine rotor speed is a function of burner outlet pressure, engine intake pressure, and power losses internal to the engine.

The thrust force is the reaction to eject the exhaust gas. The exit velocity is dependent on the burner outlet conditions, rate of mass flow through the burner, and the turbine rotor speed.

A generalized diagram of the functional relationships of the engine system is shown in Figure 4.3.2.4.

Ground start, ram air start, and rundown are to be simulated using performance data from tests. Malfunctions (or instructor control features) will be provided to simulate hot start and slow start.

FIGURE 4.3.2.4
AIR BREATHING ENGINE SYSTEM



Instrumentation and signal conditioning will be accomplished to the simulated parameters prior to display to the crew members. The parameters will be conditioned using sensor and display booleans from the Electrical Power Subsystem for crew station display, input to the Caution and Warning Subsystem, and input to the Telemetry Subsystem Multiplexer System.

The equations of the Air Breathing Engine Subsystem will be repeated for each engine, tank, and throttle system either by programmed loops or by repetitive equations. Required malfunctions of the system will be designed into the simulation model for minimum computer impact.

The inlet atmospheric conditions and ram air effects are to be simulated by the following general equations:

1) Ideal ram pressure:

$$P_{T2_1} = f(P_{AMB}, M_{ACH})$$

$$N_R = f\ (M_{ach}, AOA)$$

2) Compressor face pressure

$$P_{T2} = f(N_R, P_{T21})$$

3) Pressure correction factor

$$\delta T_2 = K \cdot P_{T2}$$

4) Temperature correction factor

$$\theta_{T2} = T_{T2}/T_{SL}$$

The speed/fuel control effects are given by:

5) Control reference speed

$$N_{CR} = f(\delta_{THR}, P_{T2}, T_{T2}, Mach)$$

6) Acceleration Schedule

$$W_f/P_{bACC} = f(N_2, T_{T2}, \delta_{THR})$$

7) Fuel Metering

$$W_f/P_b = K_{GD} (N_{CR}-N_2)$$

8) Metered fuel flow

$$W_{fm} = (W_f/P_b * P_{BX} * \delta_{WFESC}$$

or

$$W_{fm} = (W_f/P_b * P_{BX} * \delta_{FESC}$$

9) Engine function

$$K_T = f[N_2, P_b, T_{T2}, (W_{fm}-W_{fss})]$$

10) Electronic Control

$$\delta_{wfesc} = f(FT1T - FT1T)$$

$$\delta_{V1GV} = FAN - f(N_1)$$

11) Rotor Acceleration

$$\dot{N}_2 = f[(W_{fm}-W_{fss}), K_T]$$

12) Rotor Speed

$$N_2 = \int \dot{N}_2 dt$$

The oil pressure of the engine is a function of the rotor speed and temperature.

13) Oil Pressure

$$O.P. = f(N_2, T_{T2})$$

The fuel management will be calculated from fuel usage.

14) Fuel Quantity

$$W_f = W_f - W_{fm}$$

The engine parameters are calculated by the following general equations:

15) Engine pressure ratio

$$EPR = f(N_2, MACH, \delta_{BL}, \delta_{V1GV})$$

16) Engine Burner Pressure

$$P_b = f(EPR, Mach, \delta_{BL}, \delta_{T2})$$

17) Low Pressure Rotor Speed

$N_1 = f(EPR, MACH, \delta_{BL}, \sqrt{\theta_{T2}})$

18) Fan Turbine inlet temperature

$FTIT = f(EPR, MACH\ \delta_{BL})$

19) Steady State fuel flow

$W_{fss} = f(EPR, MACH, \delta_{BL}, \delta_{T2}, \sqrt{\theta_{T2}})$

20) Bleed Air

$\delta_{BL} = f(\delta_{A/C}, \delta_{A/I})$

The thrust force is then calculated by:

21) Nozzle Pressure

$P_{NOZ} = f(EPR, MACH, \delta_{BL}, P_{AMB})$

22) Net Propulsive Thrust

$F_N = f(P_{NOZ}, W_{FM})$

Following these looped equations for the four engines, the parameters would then be conditioned for transfer to displays or other software programs such as Caution and Warning or Telemetry.

AOA	Aircraft angle of attack
EPR	Engine pressure ratio
FN	Engine thrust
FTIT	Fan turbine inlet temperature
K_{BCB}	Burner cutback constant
K_{τ}	Engine time constant coefficient
MACH	Mach number
N_{CR}	Control reference speed
$\dot{N}_2$	High-pressure rotor acceleration
N_2	High-pressure rotor speed
O.P.	Engine oil pressure
P_{AMB}	Ambient pressure
P_b	Engine burner pressure
P_{bx}	Control reference burner pressure
P_{NOZ}	Convergent nozzle total pressure
P_{T_2}	Compressor face total pressure
P_{T2I}	Ideal compressor face total pressure
T_{SL}	Sea level ambient temperature
T_{T2}	Compressor face total temperature
W_{fm}	Gas generator metered fuel flow
W_{fss}	Gas generator steady state fuel flow
W_{ft}	Total fuel flow
W_f/P_b	Fuel flow metering parameter
δ_{VIGV}	Variable compressor geometry effect

$\delta_{A/C}$	Air-conditioning and utility bleed load
$\delta_{A/I}$	Anti-ice bleed load
δ_{BL}	Total bleed load increment
δ_{THR}	Throttle angle
δ_{T2}	Total compressor inlet pressure ratio
θ_{T2}	Total compressor inlet temperature ratio

4.3.2.5 Solid Rocket Motor Subsyste

The Solid Rocket Motor System will be simulated by use of performance data tables. The data that must be matched most closely is from the reference trajectory data. The method requiring the least amount of computer time with a high accuracy is a table look-up and interpolation between points of the table for immediate time values. The suggested table will be composed of thrust, mass, mass position, and moment of inertial data stored at fixed time intervals. The time related parameters will be based on time from SRM ignition.

The thrust and mass interpolation equations block shown in Figure 4.3.2.5 will perform the table look-up of interpolation constants approximately once every second. In between table values, the program equations will compute interim parameter values. The computer parameters will be modified for off-nominal performance of the two SRM engines using instructor entered modifiers. These modifiers will allow the simulation to depict grain checking, sloughing, and contamination resulting in slow burning of propellants. The equations will generate parameters to simulate audio cue devices for the engine sound/vibration. Thrust termination will generate audio cues for explosive devices and visual cues for the thrust termination ports. Thrust and mass parameters will be simulated

by curve fit equation. The equation will be modified by time since rocket ignition.

The calculation of thrust, mass, moment of inertia, and c.g. location will be accomplished by table lookup as a function of a modifiable time base, T. The instructor will be able to increase or decrease the burn time of the engine by modifying the T base.

$$T = f(t, I_c)$$

$$\text{and } T_F = f(T)$$

$$M = f(T)$$

$$I = f(T)$$

$$X = f(T)$$

$$Y = f(T)$$

where T = relative time position of table data

t = time since ignition

I_c = instructor modifier

T_F = Thrust Force

M = Mass of rocket engine

I = Moment of inertia of rocket engine

X = X body position of c.g.

Y = Y body position of c.g.

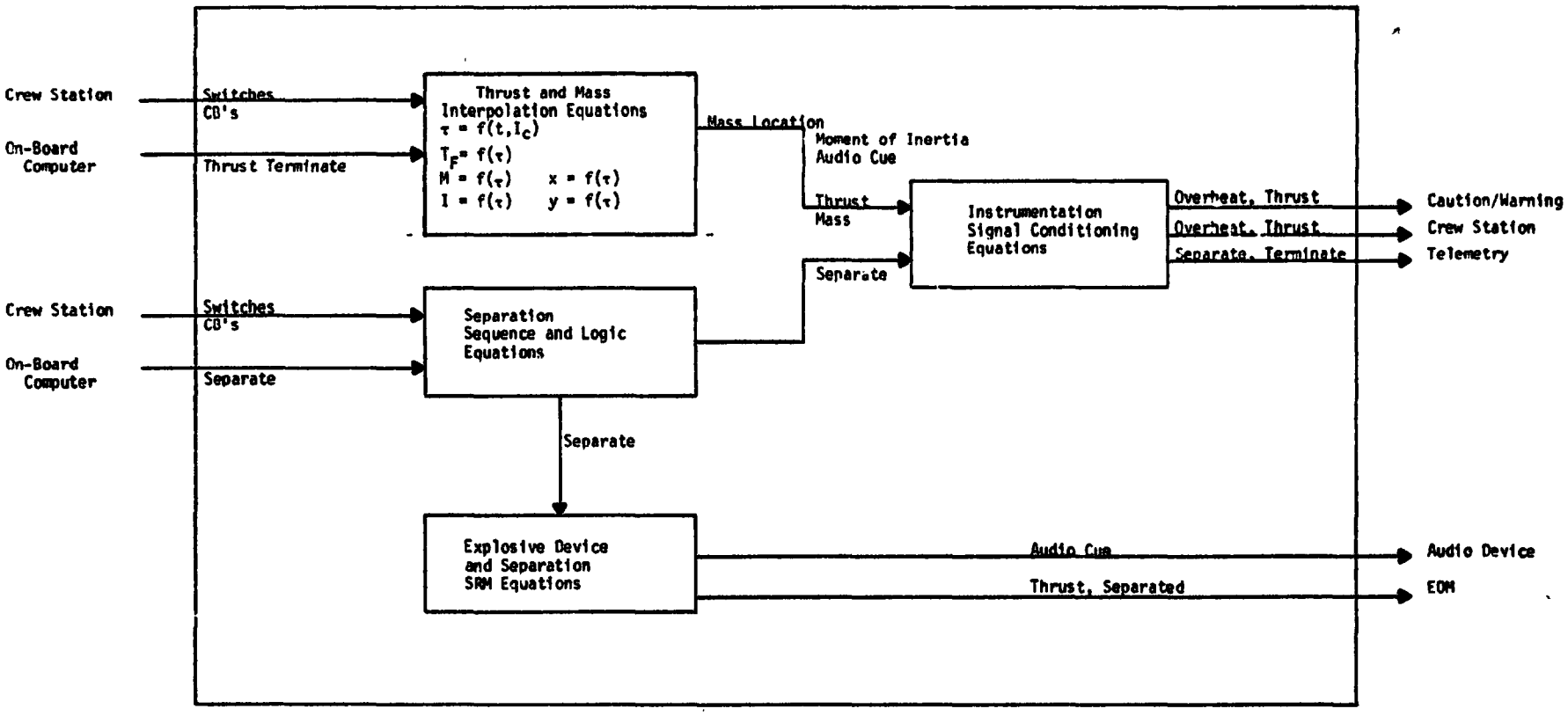
The simulation of the sequential logic and mechanical functions for separation will be accomplished by logic equations. These equations will take into account explosive device armament by the crew and separation cues either by switch command or On-Board Computer inputs.

The explosive device equations will provide an audio cue, a cue to EOM indicating physical separation, and a cue to the separation SRM engines to ignite.

The separation SRM equations will provide the thrust forces of the small rockets to the EOM program for the new "target" vehicles. Once the separation SRM has burned out, this program is no longer computed

The instrumentation and signal conditioning equations accept parameters simulating the actual system state and condition these parameters using sensor and display logic booleans from the Electrical Power Subsystem for crew station display, for input to the Caution and Warning Subsystem, or for input to the Telemetry Subsystem Multiplexer Program. The equations will be repeated for each Solid Rocket Motor unit, either by programmed loops or by repetitive equations, whichever requires the least amount of computer time and core. Required malfunctions for the SRM simulation are to be designed into the simulation for minimum computer impact.

4.3.2.6 Solid Rocket Motor Subsystem



4.3.3 Vehicle Configuration System

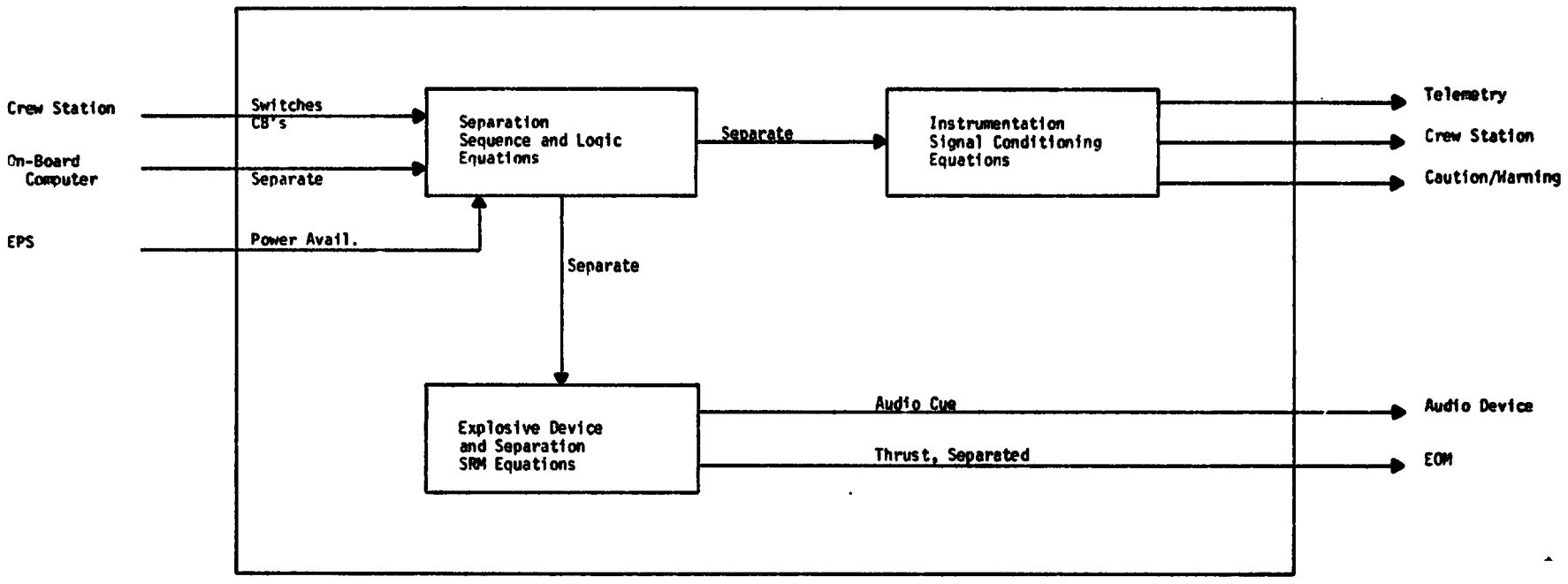
4.3.3.1 External Tank Subsystem

The simulation of the sequential logic and mechanical functions for External Tank System separation will be accomplished by logic equations. These equations will take into account explosive device armament by the crew and separation cues either by switch command or On-Board Computer inputs.

The explosive device equations will provide an audio cue, a cue to EOM indicating physical separation, and a cue to the retro SRM engines to ignite. The retro rocket ignition cue will be based on the simulated external tank avionics state and separation attitude and distance data calculated from EOM attitude and position data. The separation SRM equations will provide the thrust force of the small rocket to the EOM program for the new "target" vehicle. Once the separation SRM has burned out, this program is no longer computed.

The instrumentation and signal conditioning equations accept parameters simulating the actual system state and condition these parameters using sensor and display logic booleans from the Electrical Power Subsystem for crew station display, for input to the Caution and Warning Subsystem, or for input to the Telemetry Subsystem Multiplexer Program. Required malfunctions for the simulation are to be designed into the simulation for minimum computer impact.

4.3.3.1 External Tank Subsystem



4.3.3.2 Landing Gear Subsystem

The simulation of the Landing Gear Subsystem can be primarily considered best suited for logical equation solutions. Logical sequential functions will be simulated as time dependent parameters. The system may be divided into the four related groups of equations as shown in Figure 4.3.3.2.

The equations for gear deployment and retraction consider electrical power through switches and circuit breakers to the hydraulic servo valves used to unlock/lock, open/close wheel well doors, and raise/lower the landing gear. Time sequential delays will be incorporated into the equations to simulate the hydraulic power factor. A low hydraulic power factor will cause an increase in the time required for the hydraulic activator to move to the end position. A load parameter will be generated for the Hydraulic Power Subsystem. Gear-up and Gear-down parameters will be generated for use by other landing gear equations, and for display in the crew station. Drag force cues for gear and doors will be calculated for use by the Aerodynamic Forces Subsystem.

The equations of the landing force equations will take into account the EOM data for groundspeed rate of descent, position above the runway surface, and vehicle attitude to calculate the forces at each gear for the EOM program. Audio cues will be generated for touchdown of each gear. The oleo pressure and shock absorber deflection of each gear will be taken into account during landing and rollout so that the resultant position of the vehicle above the runway is realistic.

Steering forces for deflection of the vehicle from nose wheel attitude will be calculated for input to the EOM program. The position

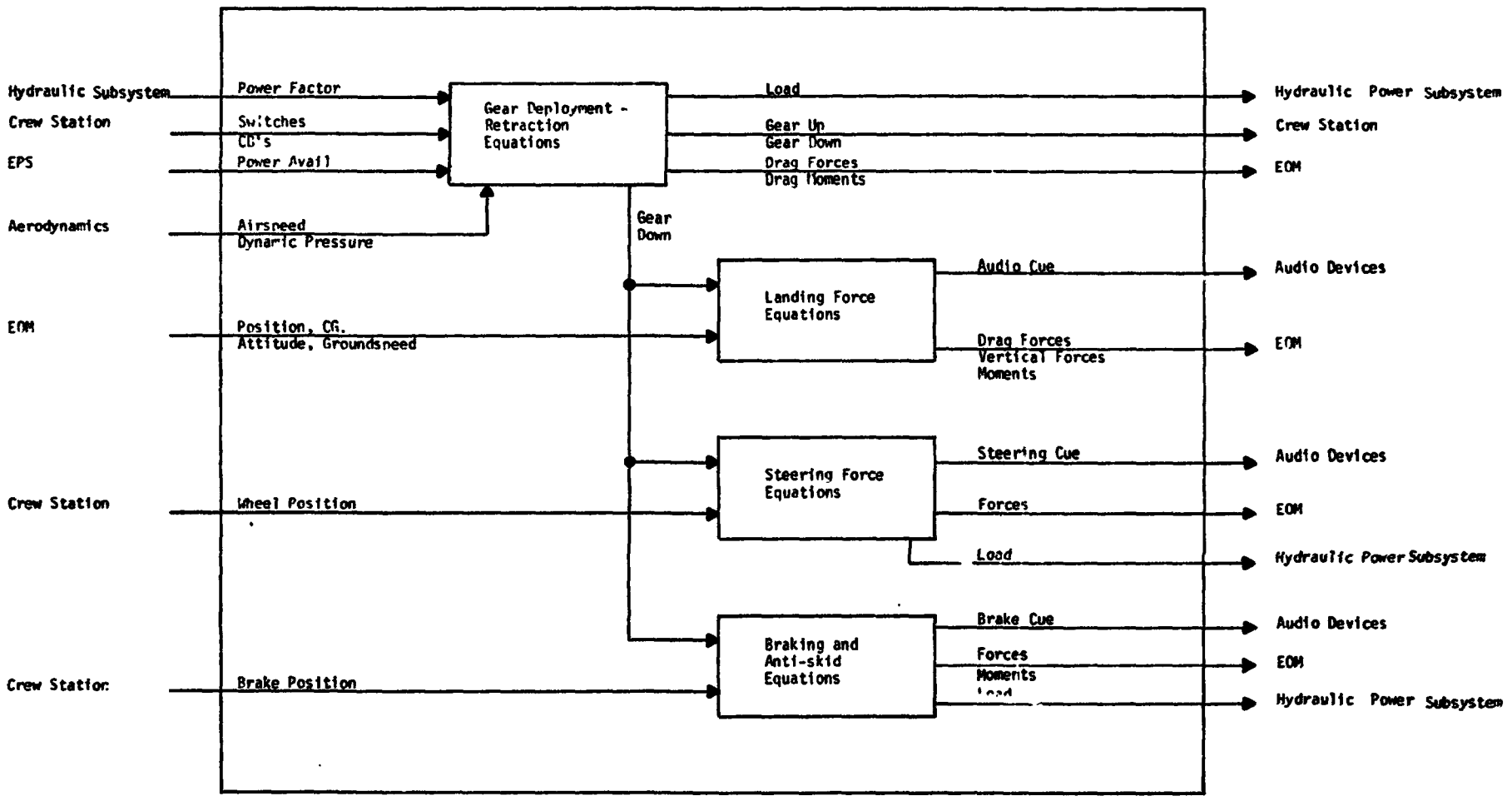
of the nose wheel will be calculated based on inputs from the crew station and the hydraulic power factor time response. Cues will be generated for audio indication of nose wheel steering movement including nose wheel shimmy. Hydraulic fluid usage load will be generated for the Hydraulic Power System.

The Braking and Anti-Skid equations will generate the horizontal braking force applied to each gear wheel set. Anti-skid system braking forces will be generated using simulated wheel rpm and the ground speed of the vehicle. Cues will be generated for the audio devices indicating braking of the carbon-on-carbon surfaces.

Off-nominal landing effects from water, ice, defective systems, etc., will all be instructor controlled inputs as malfunctions.

From these groups of equations, parameters simulating the actual system state will be conditioned using sensor and display logic booleans from the Electrical Power Subsystem for crew station display, for input to the Caution and Warning Subsystem, or for input to the Telemetry Subsystem Multiplexer Program, if applicable. The equations will be repeated for each landing gear unit, either by programmed loops or by repetitive equations, whichever requires the lease amount of computer time and core. Required malfunctions for the landing gear are to be designed into the simulation for minimum computer impact.

4.3.3.2 Landing Gear System



4.3.3.3 Drag Chute Subsystem

The drag chute will require a minimum logical simulation approach. Chute deployment logic will be computed from electrical power available, circuit breaker, and switch state. Following deployment, the chute drag force will be generated based on vehicle airspeed and the distance of the chute centerline above the ground. The logic of chute release will be nearly identical to the chute deployment equation. Parameters used for display or as inputs to the Caution and Warning or Telemetry programs will be signal conditioned with sensor power booleans from the Electrical Power Sub-System. The malfunctions for the drag chute simulation are to be designed into the simulation for minimum computer impact.

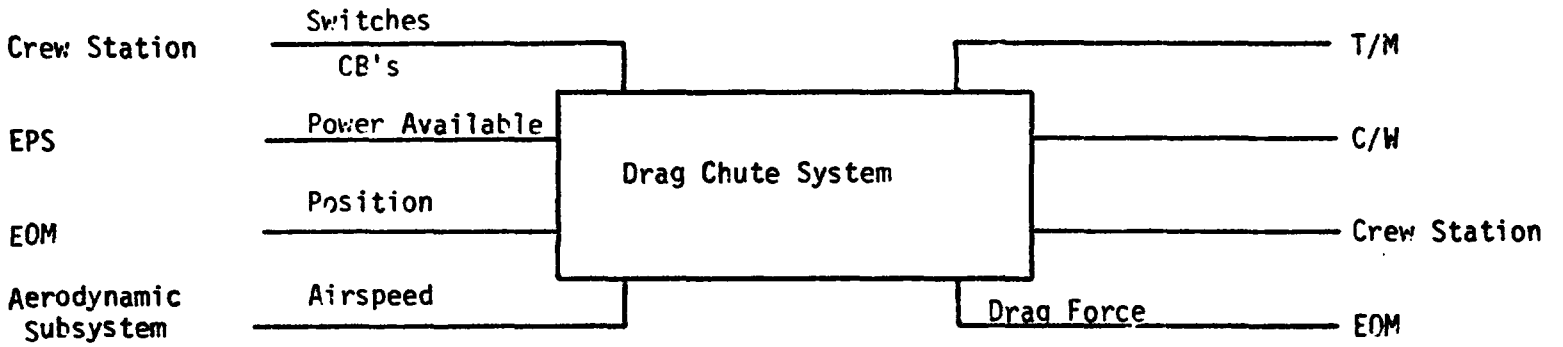


Figure 4.3.3.3

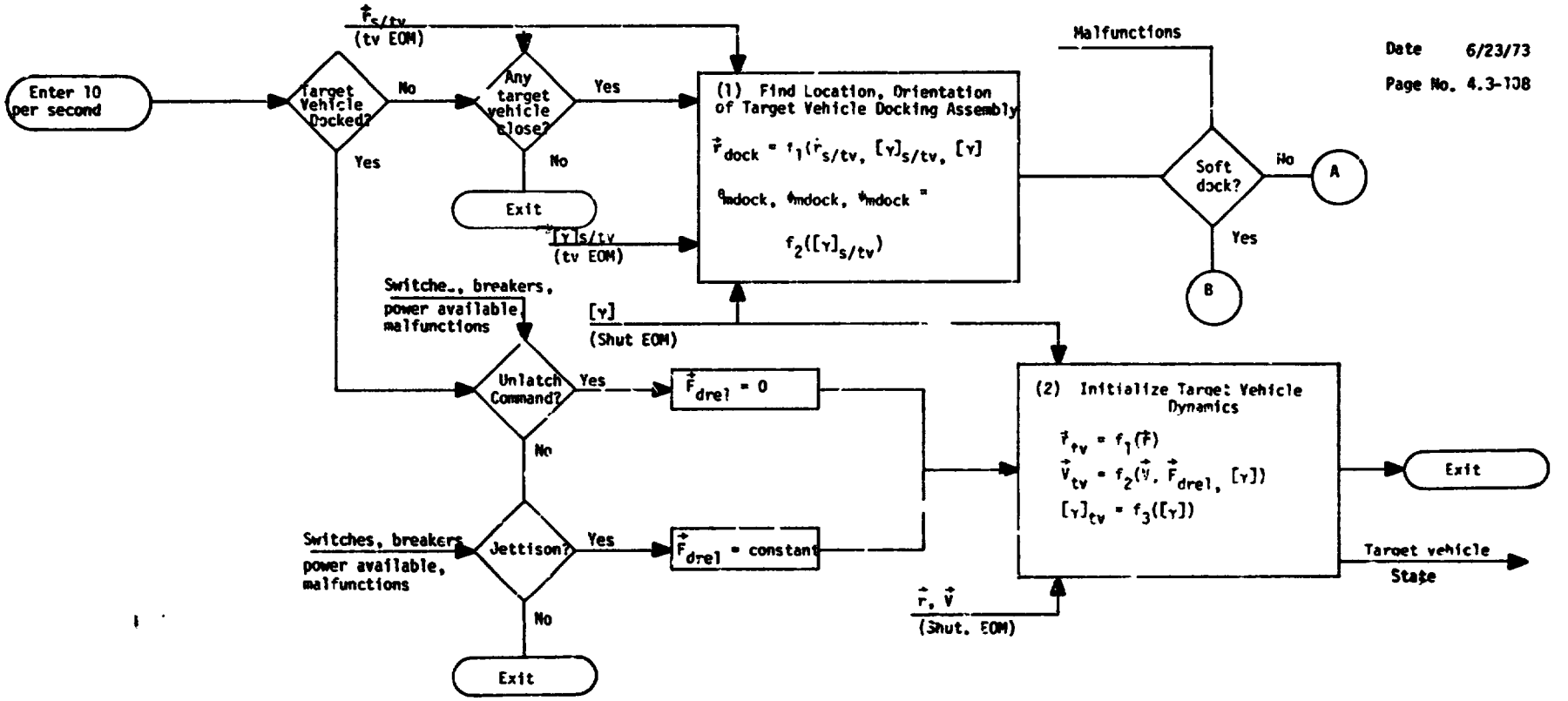
DRAG CHUTE SUB-SYSTEM

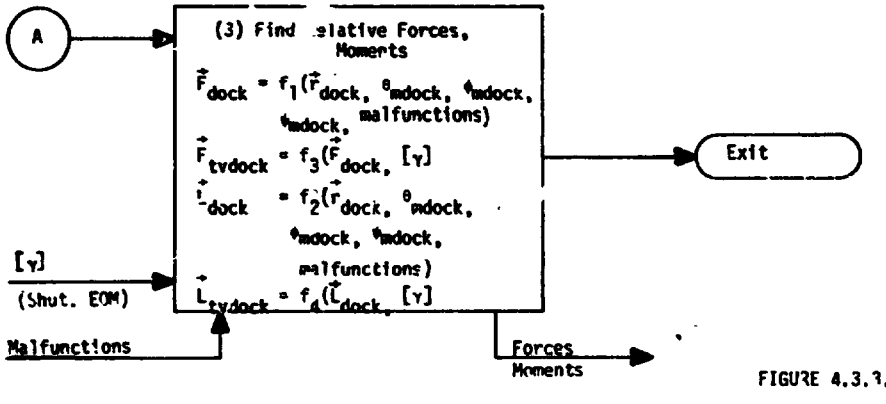
DATE 6/23/73
REV.
THE SINGER COMPANY
SIMULATION PRODUCTS DIVISION
BINGHAMTON, NEW YORK
PAGE NO. 4.3-105
REP. NO.

4.3.3.4 Docking Subsystem

The simulated docking subsystem will simulate the operation of the shuttle docking mechanism. Inputs to the system will include the shuttle-to-target vehicle position vector (target vehicle translational EØM), shuttle-to-target-vehicle direction cosines (target vehicle rotational EØM), shuttle vehicle direction cosines (shuttle rotational EØM), and instructor inputs (malfunctions, etc.). Outputs will include forces and moments upon both the shuttle vehicle and target vehicle exerted by the docking mechanism. The docking mechanism is assumed to be deployable, and to be operative only when deployed. The device will be simulated accordingly. If deployment requires a noticeable finite time, and if this effect is visible to the crew, the simulated mechanism will also exhibit a similar finite deployment time. State information for the two vehicles will be used to calculate the relative positions and attitudes of the two docking devices. The particular configuration of the docking device present on a given mission will be simulated. Depending on present relative state (and docking mechanism configuration), forces and moments upon both vehicles due to the operation of the guide cone, actuators/attenuators, or alignment rings are calculated. When relative position and attitude (and malfunction status) is proper, capture latches will be simulated to be closed, and resulting forces and moments will be calculated. Hard dock will be simulated to occur when the proper relative state exists (and malfunctions have not rendered it impossible). Upon hard dock, a boolean will be set to cause target vehicle mass properties to be included with shuttle mass properties. Unlatching of a docked vehicle will be simulated as occurring upon remote command, providing relevant switches and breakers are properly configured, power is available, and the system has not been malfunctioned in such a way as to prevent release. Upon release, target vehicle EØM will be

reinitialized from shuttle EØM. The fail-safe docking device jettison ordnance will be simulated for emergency use. An update interval of 100 milliseconds is used for the docking subsystem simulation, which matches the update rate for target vehicle EØM. The conceptual design for the simulation of the docking subsystem is sketched in Figure 4.3.3.4.-1.





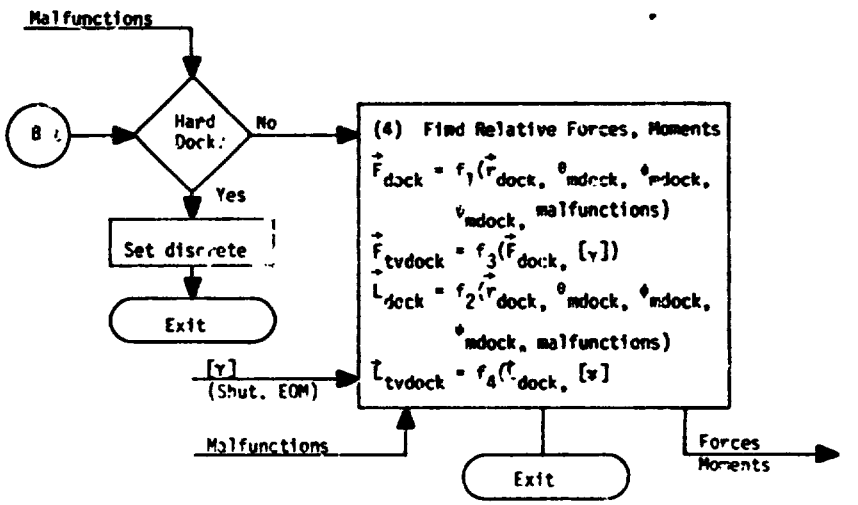


FIGURE 4.3.3.4.-1

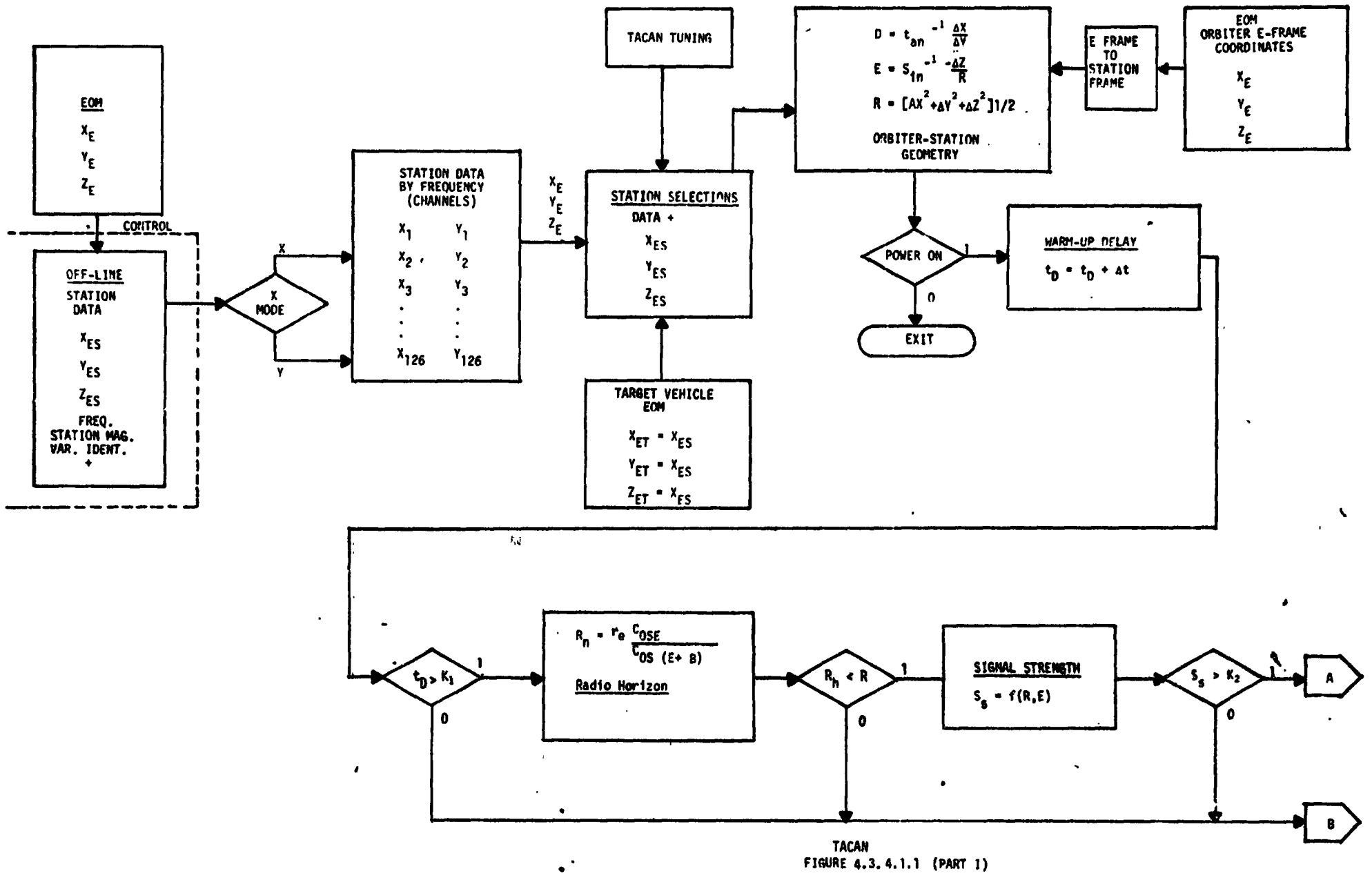
Symbol Dictionary for Figure 4.3.3.4.-1

$\vec{F}_{dock}$	force exerted by docking mechanism on shuttle	$[\gamma]$	shuttle attitude direction cosines
$\vec{F}_{drel}$	unlatching/jettisoning impulse	$[\gamma]_{s/TV}$	shuttle body to target vehicle body direction cosines
$\vec{F}_{TVdock}$	force exerted by docking mechanism on target vehicle	$[\gamma]_{TV}$	target vehicle attitude direction cosines
$\vec{L}_{dock}$	torque exerted by docking mechanism on shuttle	θ_{mdock}	pitch docking misalignment
$\vec{L}_{TVdock}$	torque exerted by docking mechanism on target vehicle	ϕ_{mdock}	roll docking misalignment
$\vec{r}$	shuttle inertial position		
$\vec{r}_{dock}$	relative position of target vehicle docking assembly (shuttle body-fixed coordinates)	ψ_{mdock}	yaw docking misalignment
$\vec{r}_{s/TV}$	shuttle-to-target vehicle vector (inertial coordinates)		
$\vec{r}_{TV}$	target vehicle inertial position		
$\vec{V}$	shuttle inertial velocity		
$\vec{V}_{TV}$	target vehicle inertial velocity		

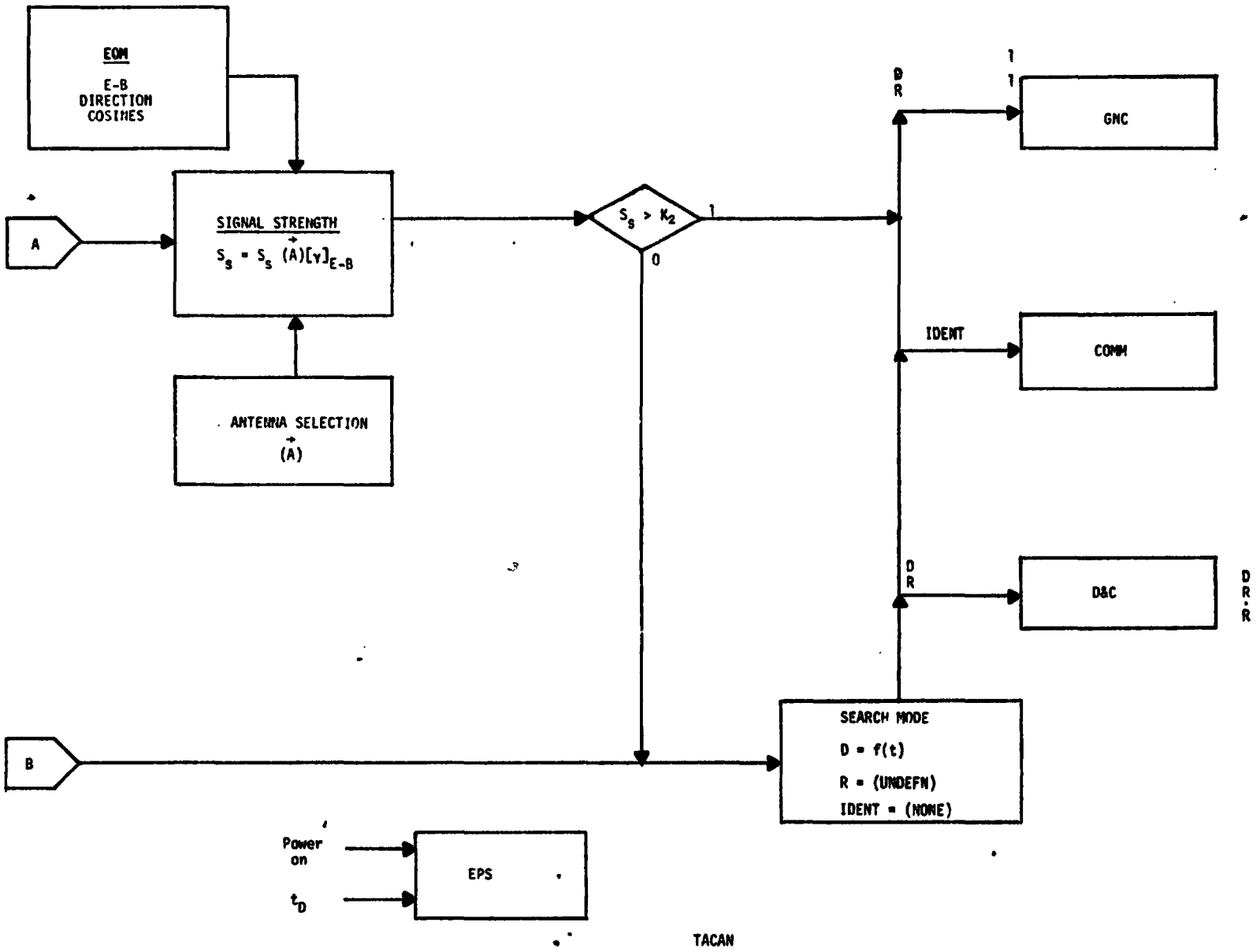
4.3.4 Communications/Tracking System

4.3.4.1 TACAN Subsystem

The Space Shuttle Subsystem contains the three TACAN Transmitter/Receivers, control panels and L band antennas located in the orbiter and makes use of existing ground TACAN facilities. The orbiter controls are located on the pilot center console and include the three 3-digit frequency selectors, the three X-Y mode switches, the three test switches and three local/master switches. The NAV AUDIO switch contains positions for monitoring the TACAN station identification signals. The TACAN Master Switch selector (3 position) and local/master switches allow advance set-up of the panel to sequentially select three stations or to obtain simultaneous information from up to three stations if in range. The X-Y mode control provides for operation on any one of 252 paired frequency channels, 126 for each position of the switch. Station identification is provided by receipt of the transmitted 1350 hz station identification call letters. The TACAN operates by flight interrogation pulsing of the ground based beacon system. There is a search mode in which the system is pulsed at a relatively high frequency. Once lock-on is achieved, the system provides bearing and distance information for use by the G N & C computer and for various displays including the Attitude Director Indicator, Horizontal Situation Indicator, and/or CRT displays. In the TACAN mode, the HSI "To/From" indicator and course deviation indicator display deviation from the selected TACAN radial. The HSI course deviation warning flag indicates deviation validity. The desired tacan radial is selected by means of the HSI course set knob and is displayed on the HSI course selector window. Tacan information and HSI selected heading information is routed to the G N & C computer.



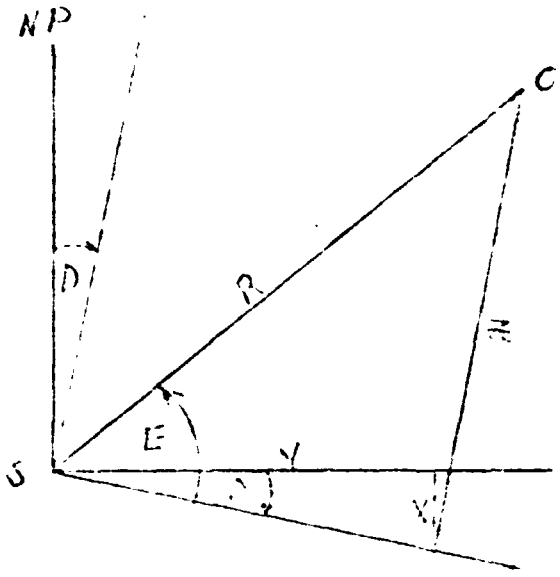
TACAN
FIGURE 4.3.4.1.1 (PART 1)



TACAN
FIGURE 4.3.1 4.1.1 (PART II)

Simulation of the TACAN subsystem includes determination of geometry between the orbiter and station selected, signal conditioning and switching logic. Two areas are somewhat, new to training simulations. These are the relatively large area coverage per unit of time and the extreme altitudes involved. In both cases the problem is one of being able to handle a large volume of station data with fast switching. Storage of this data on line would solve the technical problems but would be costly. Using off-line disc or other mass storage media, the problem is one of being able to bring the data on line as a function of switching logic (frequency, antenna selection etc.) and range. The range of trajectories allowable for shuttle missions indicate a requirement for a large number of stations. These stations will be stored off-line. EOM furnished Latitude, Longitude and Heading information will allow ordering the off-line tables in a manner to allow prediction of the area to be covered before the next update of the on-line tables. The on-line tables will be assembled by radio frequency-one set of data for each of the 252 possible selections. The station, for any one frequency, selected to be stored in the on-line table will be the station at the shortest range or strongest received signal. Refer to figure 4.3.4.1.1. As procedures for use of the Tacan become better defined, it may be found that the station data can be assembled from Reset data unique to each reset point. This would be a desirable alternative, however, provision must be made for abort and contingency modes. The latter method should be sufficient for simulation of the orbiter/detached payload mode. In this case, all necessary information can be carried as reset data except for the payload state vector which will be supplied by EOM. Once station unique data is assembled to correspond to the station selected, the simulation is straight-forward. The tacan will be in either search or track mode. In search mode, the bearing (D) will rotate and the range (R) is undefined. In track mode,

the geometry is:



$$D = \tan^{-1} \frac{X}{Y}$$

$$E = \sin^{-1} \frac{-Z}{R}$$

$$R = [X^2 + Y^2 + Z^2]^{1/2}$$

FIGURE 4.3.4.1.2

To this, signal conditioning is applied for range attenuation vehicle attitude (antenna selection), radiation pattern and radio horizon. The visibility due to radio horizon can be expressed as

$$R_h = r_e \frac{\cos E}{\cos (E+B)}$$

where R_h = radio horizon range

r_e = earth radius

E = Flevation angle constraints (default value of zero).

B = central angle between the Tacan station and the orbiter positions

B = $\sin^{-1}$ ($\bar{U}_R$ Shuttle X $\bar{U}_R$ Tacan)

The test for visibility with respect to the radio horizon between the orbiter and the Tacan station is:

$R_h < R_{orbiter}$ → visible

$R_h > R_{orbiter}$ → not visible

See figure 4.3.4.1.1

The TACAN simulation will include the "cone of confusion" over the ground station and the built in test checks.

SYMBOL DICTIONARY

X_E, Y_E, Z_E } Rotating earth centered coordinates of the shuttle vehicle.

X_{ES}, Y_{ES}, Z_{ES} } Rotating earth centered coordinates of the station.

td = Time delay

D = relative azimuth angle

E = relative elevation angle

R = LOS range

R_h = radio horizon

S_s = Signal strength

$\vec{A}$ = Antenna geometry vector

4.3.4.2 ILS Subsystem

The space shuttle ILS subsystem contains triple redundant ILS glide slope, localizer and marker beacon receivers with one frequency selection. The receiver is selected by one of three toggle switch on-off controls which also has test positions. Audio selection is made by one of the same multi-position rotary switch as used for the TACAN subsystem.

Simulation of the ILS subsystem includes geometry of the radiated signal patterns for the localizer glide slopes and the marker beacons. A unique problem to the simulation is the requirement for two nominal glide slopes, simulated simultaneously. These will have slopes of approximately 8° and 15°. The problem is not totally new since standard glide slopes have nulls at the nominal angle E, 2E, 3E, 4E, and 5E with the 5E signal phasing the same as E (fly-to error signals). The system concept depicted in Figure 4.3.4.2.2 includes these unique features, as well as the standard geometry and switching problems which must be solved. The geometry is:

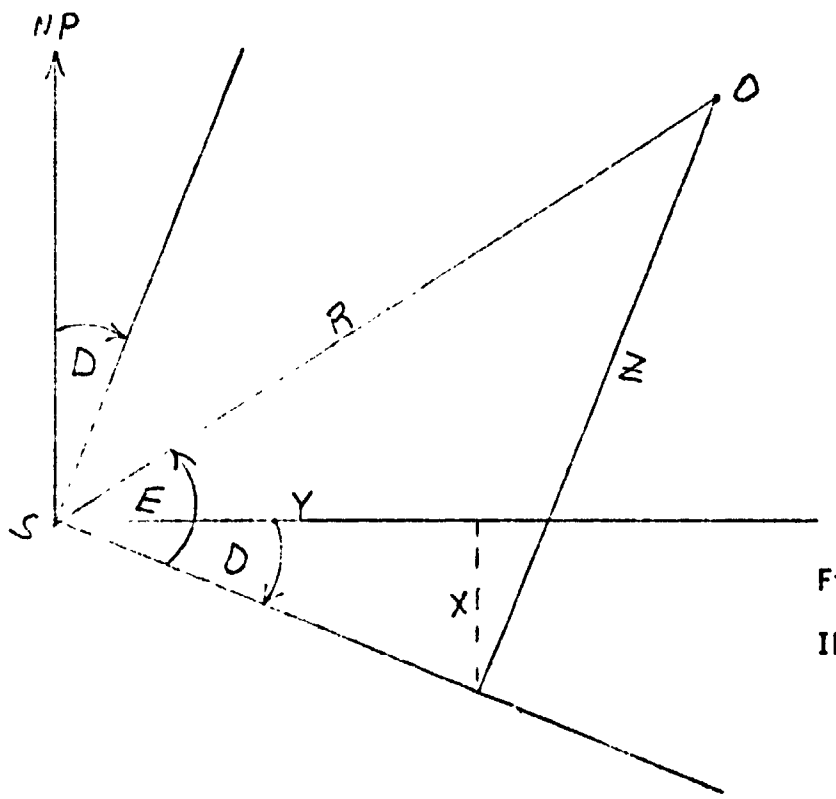
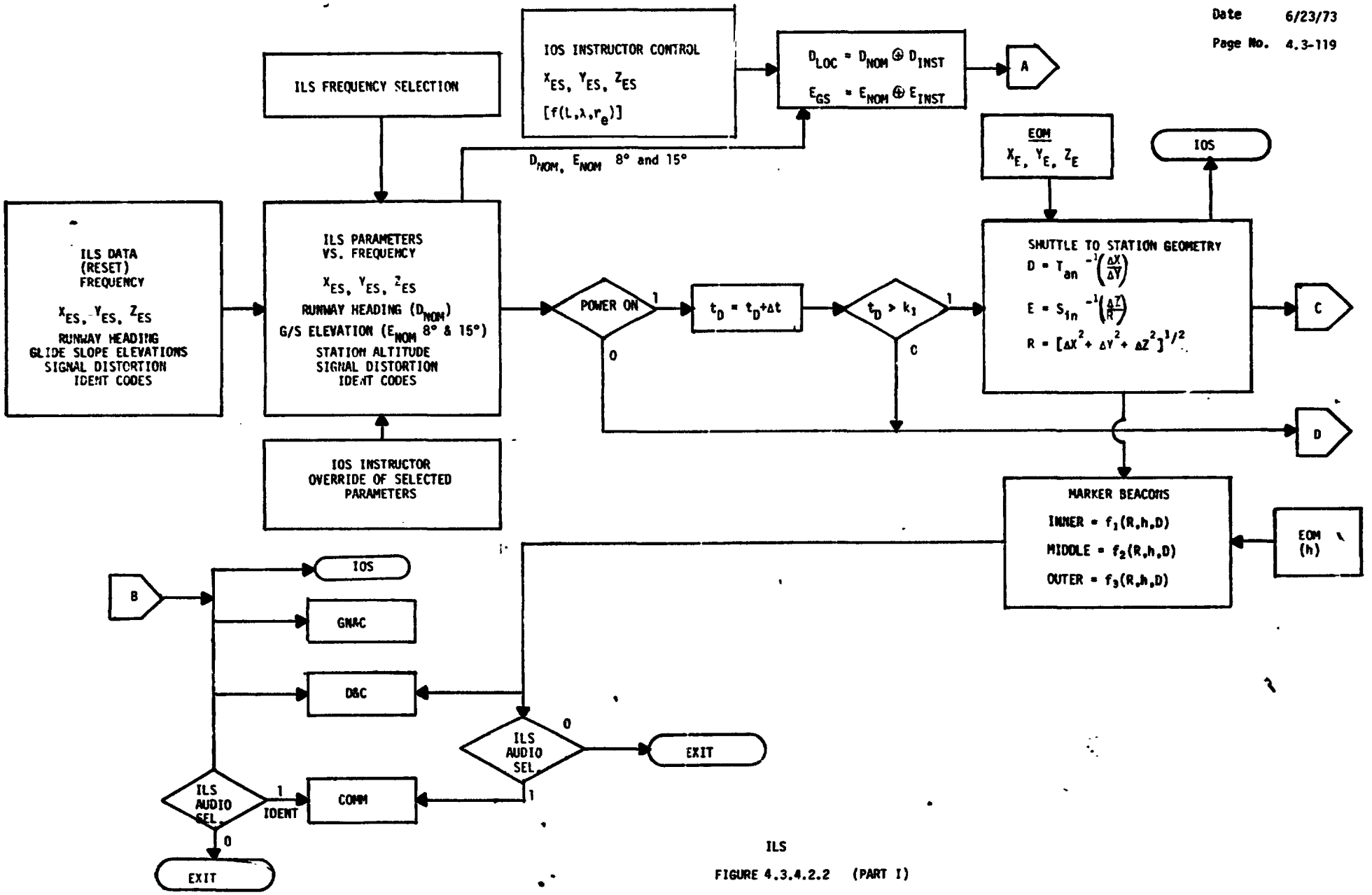


Figure 4.3.4.2.1
ILS Geometry

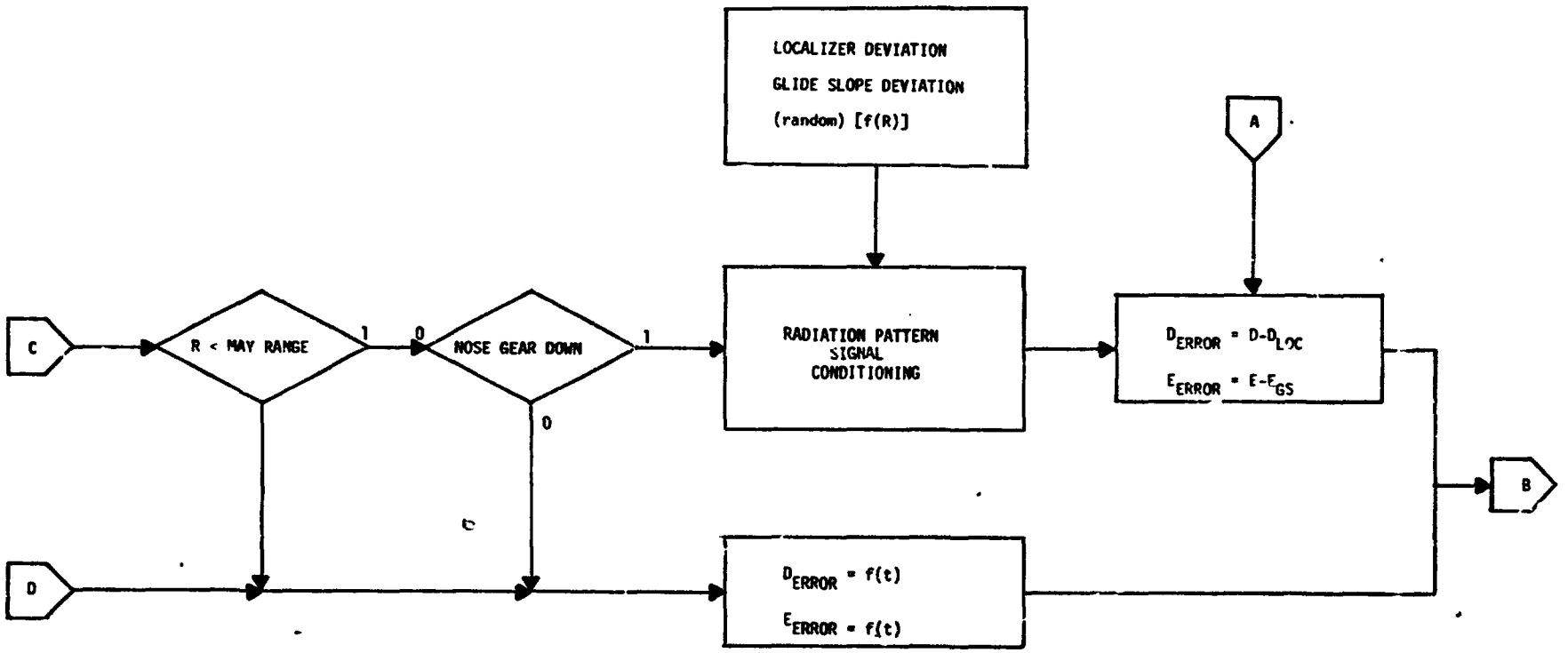
F-398.8-A

where the station azimuth angle relative to earth north is $\text{Tan}^{-1} \frac{\Delta X}{\Delta Y}$. The station-to-orbiter elevation angle is defined by the angle $\text{Sin}^{-1} \frac{\Delta Z}{R}$. An additional conditioning of the elevation error signal is required due to the multi-lobe radiated pattern and distortion of the radiated signal due to local geography and weather. The error signals generated are fly-to for the E and 5E cases and fly-from otherwise with nulls at 2E, 3E and 4E. The 8° and 15° glide slopes are assumed nominal for prime and selected alternate landing sites for the shuttle. Any other landing site would require using the 5E lobe null (with a nominal E of ∿3° for the steep glide slope). The simulation concept allows the instructor options for selection of these conditions either for space or ferry missions. Station audio identification is generated and routed to the communications system for both the ILS station and ident codes for each of the marker beacons. Aircraft systems have an indicator lamp which flashes the marker beacon code. This lamp is not known to exist on the shuttle panels, but may be part of a CRT display.



ILS

FIGURE 4.3.4.2.2 (PART I)



ILS

FIGURE 4.3.4.2.2 (PART II)

4.3.4.3 Navaids Radar Altimeter Subsystem

A typical FAA radar altimeter is assumed. This subsystem will provide warning cues as well as an accurate measurement of vehicle altitude above local terrain for display and inputs to the GN&C, COMM and D&C systems. The antennae are located sufficiently close to the vehicle center of gravity that no apparent change in indicated altitude occurs with vehicle attitude changes. Gross attitude change can, however, cause a loss of return. The logic functions shown are typical.

A local terrain software model will be constructed and data specified at the intersection of azimuth radials and range circles centered at the runway. Linear interpolation between data points will provide a smooth change in terrain altitude with the values in the tables representing exact terrain altitude at the specific points. Simulation requirements indicate a requirement for maximum accuracy at touchdown and near the nominal approach azimuth. Lower accuracy can be tolerated at long range from the landing site and at large relative bearings to the runway leadings.

Symbols and Definitions

[B-E]	B to E frame direction cosines
WOW	Weight on wheels
WDL	Wheels down and locked
h	Altitude
k	constant
h_R	Radar altitude
r	Vehicle radius to center of earth
r_o	Nominal earth radius distance exclusive of local terrain

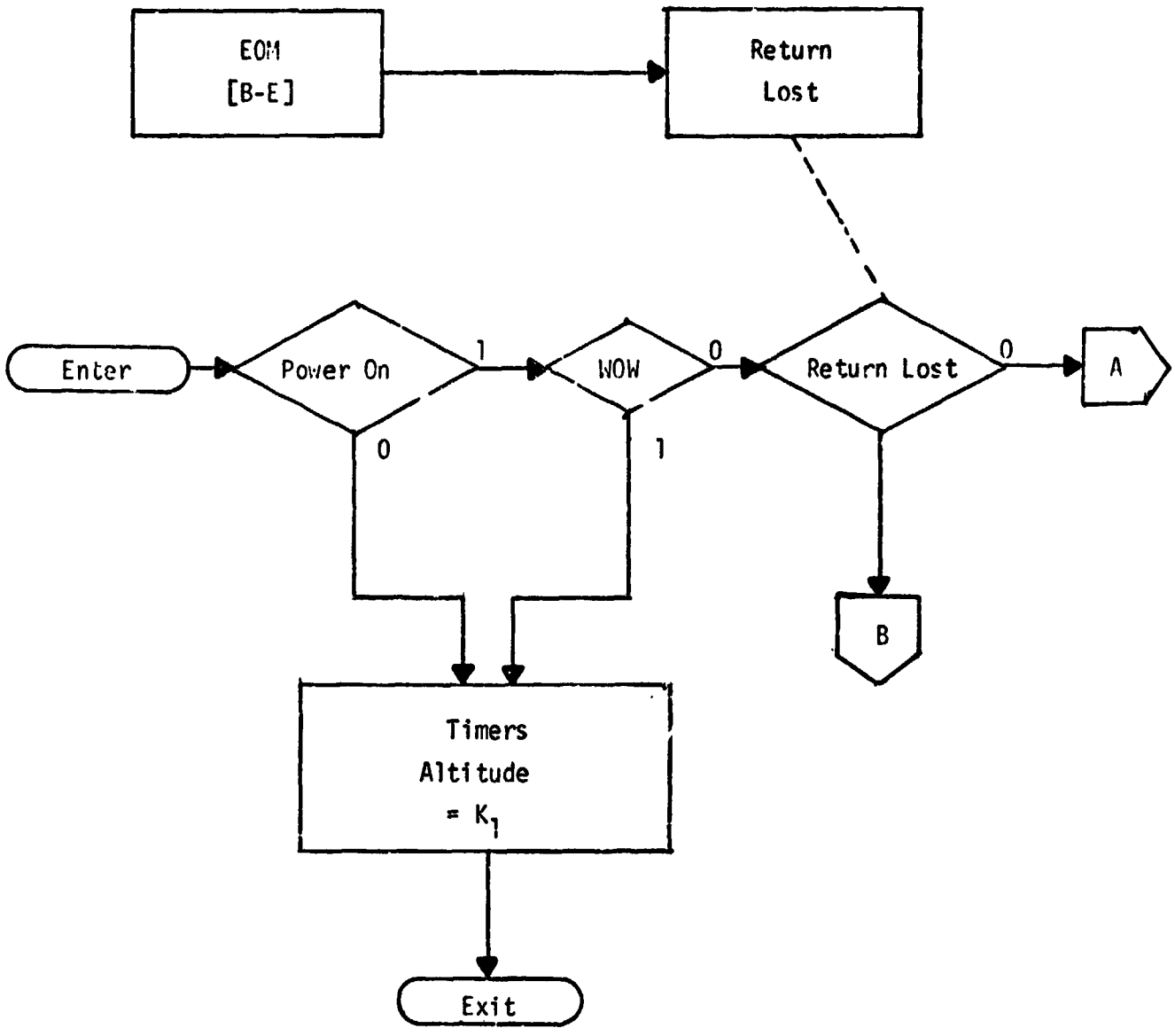


Figure 4.3.4.3 Radar Altimeter

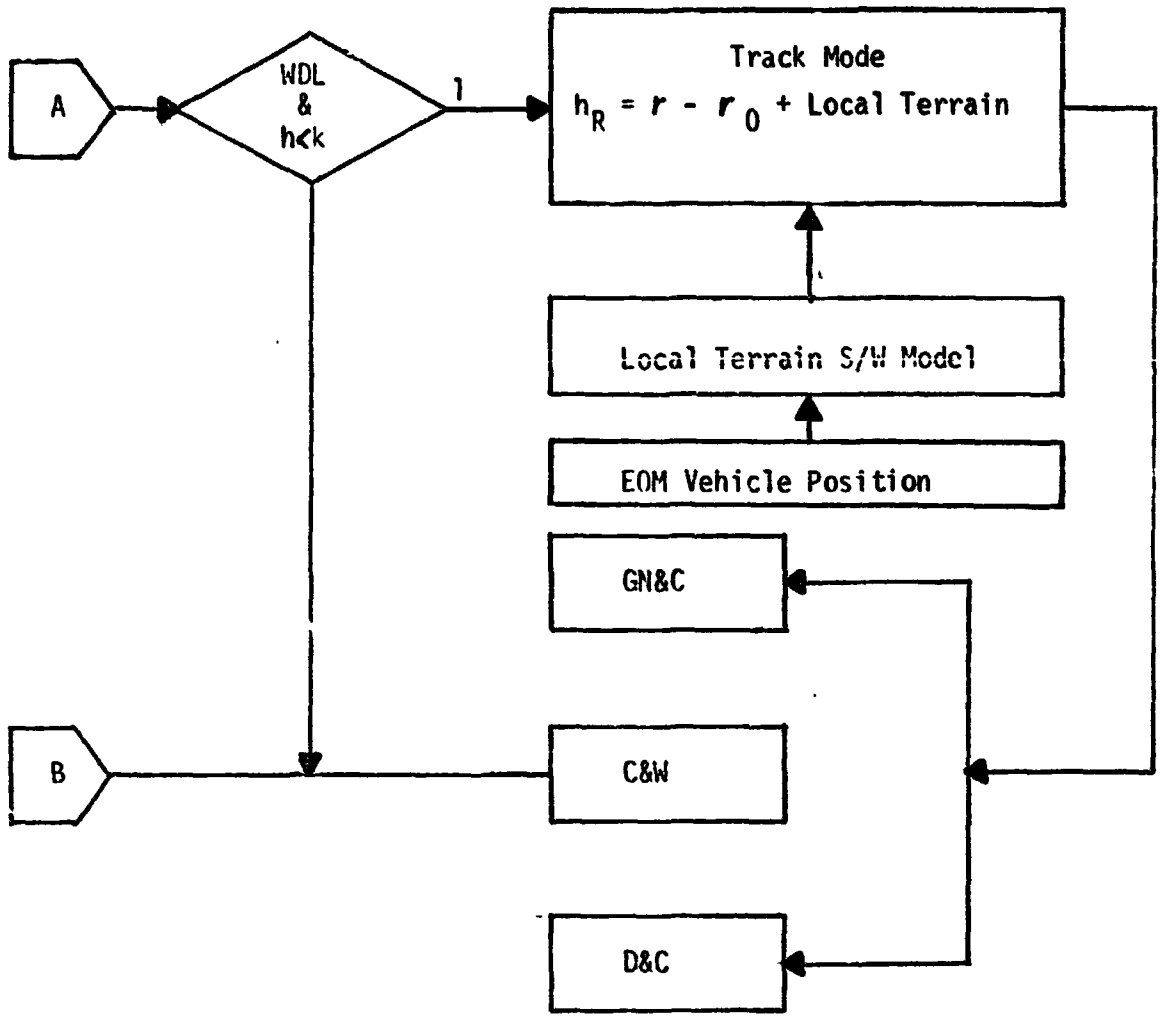


Figure 4.3.4.3 Radar Altimeter

4.3.4.4 ATC Transponder

The ATC Transponder system consists of the flight transponder with an on-off toggle switch and a toggle switch selection for transponder #1 and #2. The simulation will consist of monitors for these switches at the Instructor-Operator Station. Refer to Figure 4.3.4.4.

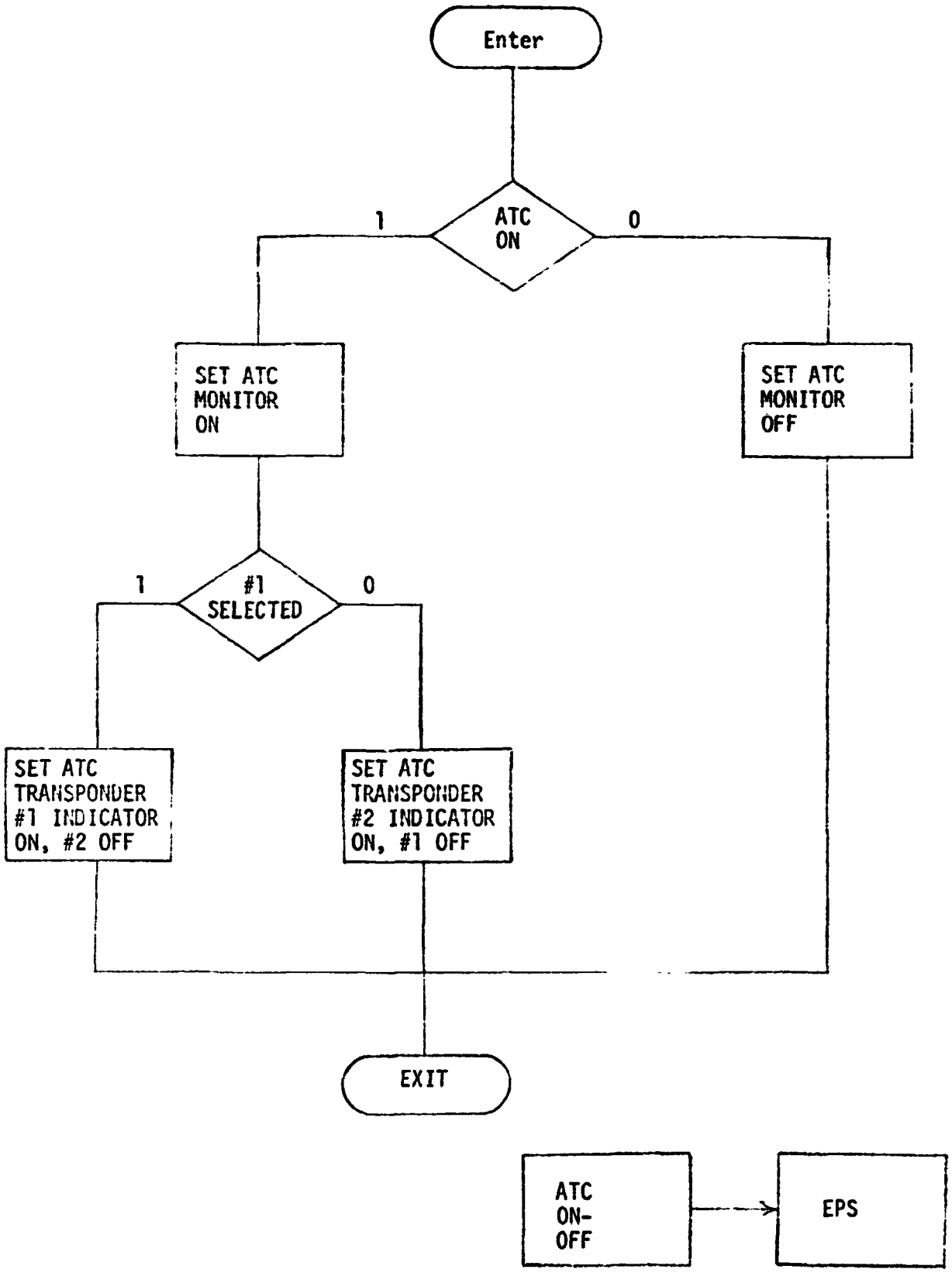

Enter
ATC ON
1
0
SET ATC MONITOR ON
SET ATC MONITOR OFF
#1 SELECTED
1
0
SET ATC TRANSPONDER #1 INDICATOR ON, #2 OFF
SET ATC TRANSPONDER #2 INDICATOR ON, #1 OFF
EXIT
ATC ON-OFF
EPS

Figure 4.3.4.4

4.3.4.5 NAVAIDS MICROWAVE LANDING SYSTEM (MLS)

The requirements of the MLS are essentially the same as for ILS (paragraph 4.3.4.2). The major differences are station frequency, orbiter controls, greater accuracy of steering information and shorter range. The conceptual design is essentially that shown for the ILS in figure 4.3.4.2. Requirements for an MLS system have not been firmly established, however the system is included in the SCD because of the probable need for a system with higher accuracy then the conventional ILS system for autolanding requirements. As of this writing, it is understood that MLS will be used.

4.3.4.6 S-Band Communication Subsystem

The simulation of the S-Band voice, data, and command communication link will be modeled by calculating the signal strength of the received signal at the vehicle and the transmitted power level. To determine the signal strength, it is necessary to determine if the signal path is occulted by earth.

The number of stations that must be tested are limited to the STDN and SGLS stations.

As shown in Figure 4.3.4.6, the line-of-sight acquisition is calculated from the vehicle position vector from EOM. Only those stations having positive elevation angles are acceptable as having line-of-sight.

The transmitter and receiver operational power is calculated from EPS power available booleans, circuit breaker state, and switch state in the crew station. Switching logic will be taken into account by the program.

Transmitter signal strength is calculated using transmitter output power attenuation losses to the antenna, and antenna gain. The transmitting-receiving antenna is determined by calculating the receiver signal strength at all antennas. In auto switching mode, the antenna with the highest signal strength is selected. This is accomplished by computing the mode of antenna selection as based on the crew panel switch positions and the calculated AGC voltage. The attenuation of the incoming signal is calculated from the attenuated ground transmitter power and the attenuation pattern of the signal from the selected antenna. The antenna pattern attenuation is calculated by performing a vehicle to Earth transformation of the EOM data yielding the relative position of the ground site to the vehicle antenna.

Following calculation of the attenuation, a background noise level will be calculated and a signal level will be calculated. These two signals will be furnished to the audio hardware equipment to generate a voice volume and a noise

volume level. Instructor override of the volume level calculated by the program will be provided.

Booleans will be generated signifying that T/M and/or DCS command capability exists. These booleans will be provided to MCC and to using subsystems.

Simulation of the phase-lock S-Band Ranging system will be provided by calculating the distance of separation of the vehicle from the ground station. This function will not require "ground station" processing by computer. The range calculated will be made available to MCC for all stations in contact with the vehicle.

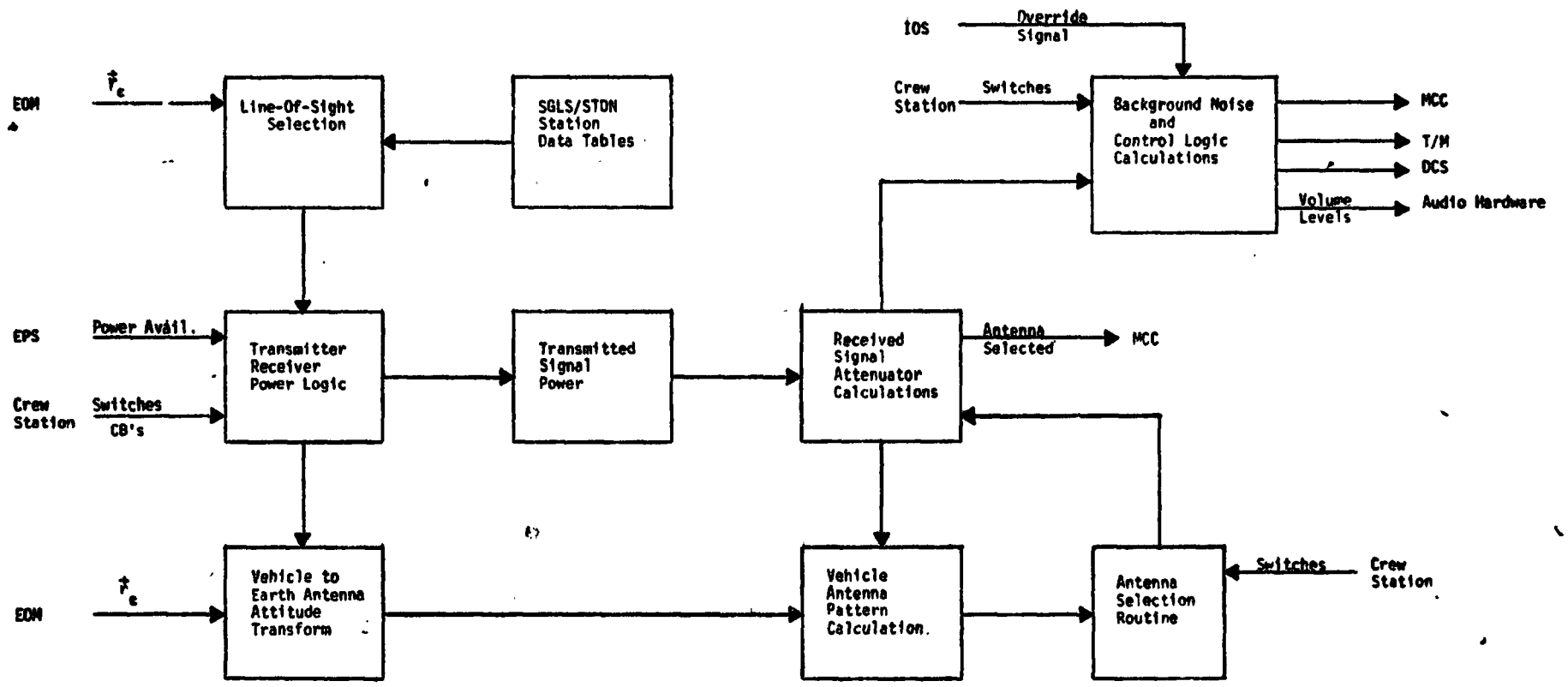


Figure 4.3.4.6

S-BAND COMMUNICATION SYSTEM

4.3.4.7 UHF Communication Subsystem

The simulation of the UHF transceiver voice communication link will be modeled by calculating the signal strength of the received signal and the transmitted power level. To determine the signal strength, it is necessary to determine if a station is occulted by earth and is operating on the correct frequency.

The number of possible stations that may be tested is limited by computer time and core. At high orbital altitudes, it becomes possible for the vehicle to have line-of-sight with large earth surface areas. The extreme example is that an area greater than the U.S. may be within line-of-sight. With such coverage, it is necessary to limit the number of ground stations loaded in working core of the computer. At this time, it is felt that twenty-five additional stations over the normal STDN stations are sufficient for any training mission. To bring these stations into core, one concept that is usable is to use the Reset feature to call from mass storage twenty-five UHF stations' parameters. Additions or deletions may be made to the Reset selected stations by providing to the instructor controlled access to the mass memory tables. These mass memory tables are expected to require approximately one-thousand stations' parameters.

In Figure 4.3.4.7, the first step in solving the UHF communication model is to calculate accessibility of line-of-sight. This is accomplished by computing the elevation angle of the vehicle. Only those stations having positive elevation angles for the vehicle are selected as having line-of-sight.

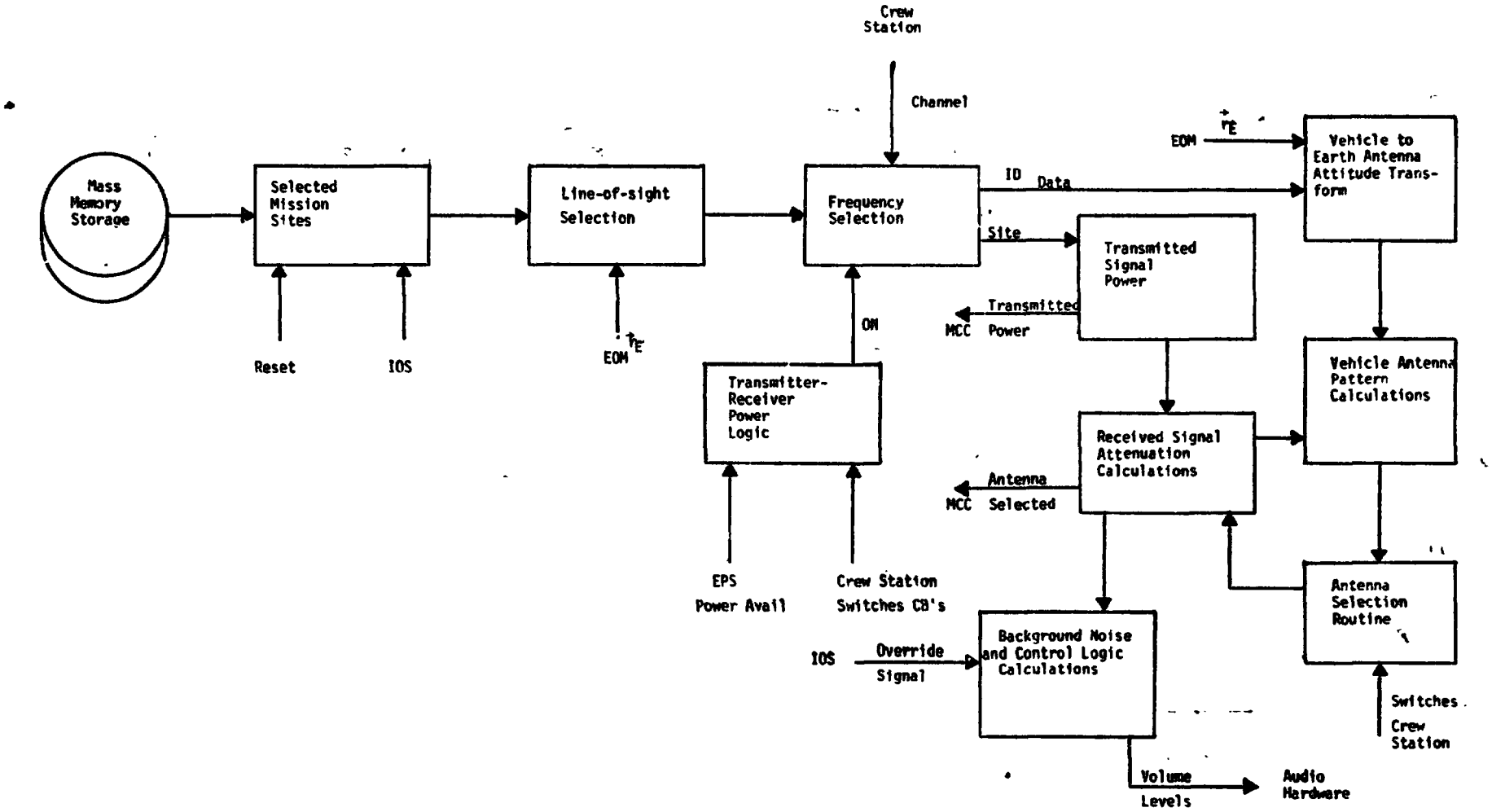
From these selected stations, the frequency (or channel) set on the crew station panels will be used to further edit the non-active stations from

the stations with positive elevation angles. Once a ground station has been identified as having both a positive elevation angle and on the same frequency as the vehicle, the station identification code, position of station in the E-frame, and the station transmitted power are provided to the transceiver power logic equations.

The transceiver power logic equations generate booleans for receiver-on and transmitter-on from the EPS power-available booleans and the crew station switch and circuit breaker control logic.

Transmitter signal strength is calculated using transmitter output power attenuation losses to the antenna, and antenna gain. The transmitting-receiving antenna is determined by calculating the receiver signal strength at all antennas. In auto switching mode, the antenna with the highest signal strength is selected. This is accomplished by computing the mode of antenna selection as based on the crew panel switch positions and the calculated AGC voltage. The attenuation of the incoming signal is calculated from the attenuated ground transmitter power, and the attenuation pattern of the signal from the selected antenna. The antenna pattern attenuation is calculated by performing a vehicle to Earth transformation of the EOM data yielding the relative position of the ground site to the vehicle antenna.

Following calculation of the attenuation, a background noise level will be calculated and a signal level will be calculated. These two signals will be furnished to the audio hardware equipment to generate a voice volume and a noise volume level. Instructor override of the volume level calculated by the program will be provided.


Crew Station
Channel
Mass Memory Storage
Selected Mission Sites
Line-of-sight Selection
Frequency Selection
ID Data
Site
EOM
Vehicle to Earth Antenna Attitude Transform
Transmitted Signal Power
Transmitted Power
MCC
ON
Reset
IOS
EOM
Transmitter-Receiver Power Logic
Vehicle Antenna Pattern Calculations
Received Signal Attenuation Calculations
Antenna Selected
MCC
EPS Power Avail
Crew Station Switches CB's
Antenna Selection Routine
IOS
Override Signal
Background Noise and Control Logic Calculations
Switches Crew Station
Volume Levels
Audio Hardware

4.3.4.8 Telemetry Subsystem

The Telemetry Subsystem for the Shuttle is simulated by supplying the GSSC-MCC complex with a serial digital data stream in a format. At this time, it is assumed that the format required by MCC for integrated training will be the same as would be received at MCC in the real-world situation. This assumption is based on previous simulation experience from SLS and CMS. The format of the multiplexed air-to-ground station telemetry data will be computed within a mini-computer for simulation purposes. The switching logic for the multiplexer and signal processors will be computed in the main computer.

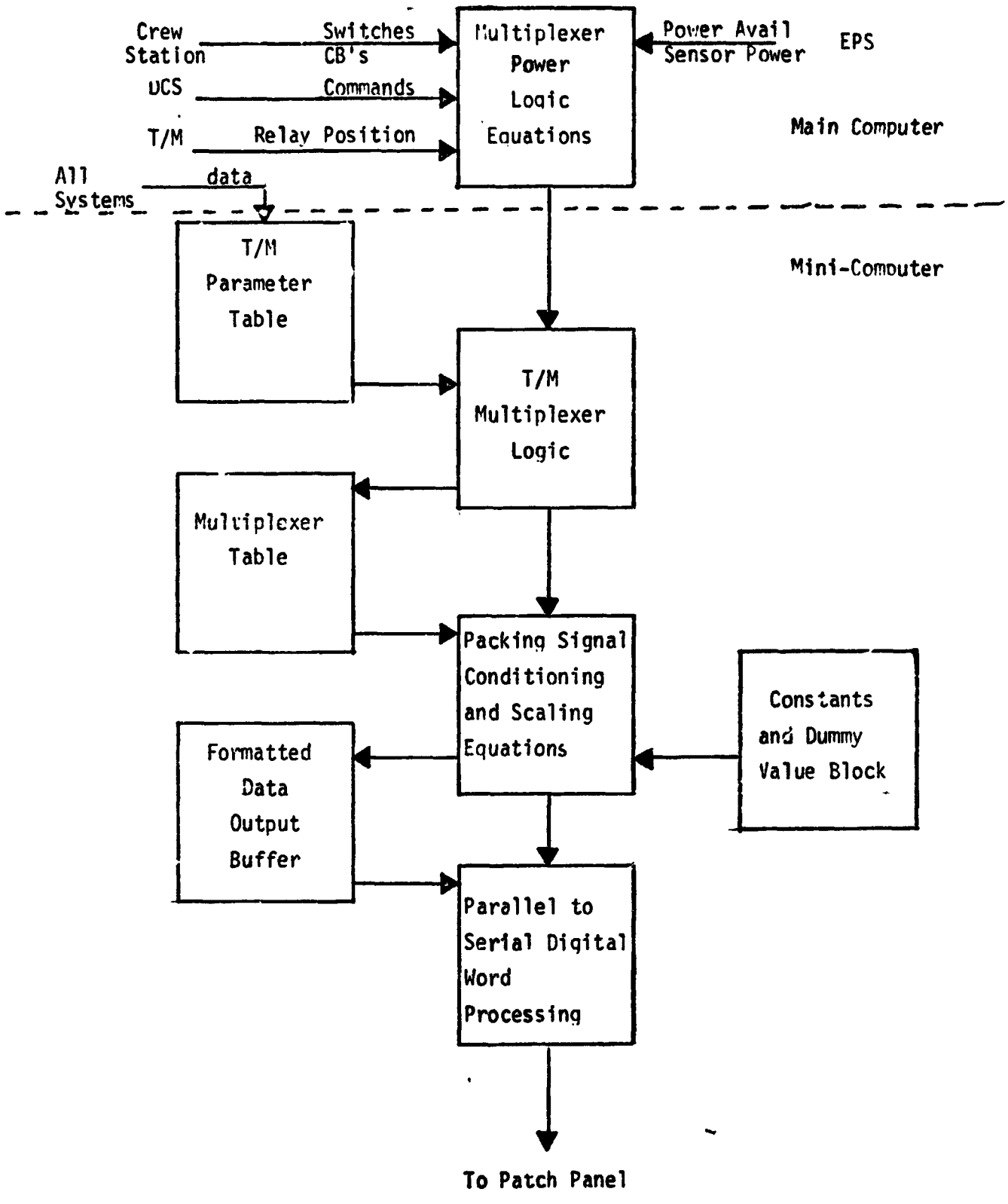
The vehicle for both OFI and DFI has a maximum data transfer rate of 128 Kbps on 1.024 MH_Z and 256 Kbps on 1.7 MH_Z. The 128 Kbps is apparently dedicated to the vehicle operation plus payload interface parameters. The 256 Kbps is payload dedicated.

The T/M simulation design concept is limited to present day equipment by NASA decision. This equipment allows a maximum Building 30 - Building 5 interface rate of 51.2 Kbps on each of two coaxial lines. This limitation reduced the T/M interface to 51.2 Kbps for the OFI and DFI instrumentation and to 51.2 Kbps for the payload digital data. The 51.2 Kbps rate is used for the two line links because the existing equipment has been used at that rate previously in the CMS Trainer.

The telemetry program functions are shown pictorically in Figure 4.3.4.8. The multiplexer power logic equations calculate the operating condition of the multiplexer and the signal conditioning units. The telemetry data will be transferred to GSSC even when the simulated T/M transmitter is inoperable. Additional booleans will be supplied to GSSC indicating the operating condition and power output of each transmitter unit from the S-Band System equations.

Telemetry parameters generated by the software systems will be stored into a table where the T/M multiplexer equations will condition the inoperative multiplexer channels with dummy values. These generated T/M multiplexer tables are then processed by the signal conditioning and scaling program. This program will take the digital floating point values and convert the data to packed words or biased, scaled, fixed point data values. These new values will then be stored into a format with the dummy filler values and constant values.

Figure 4.3.4.8 Telemetry System



F.398.8-A

4.3.4.9 Digital Command Subsystem

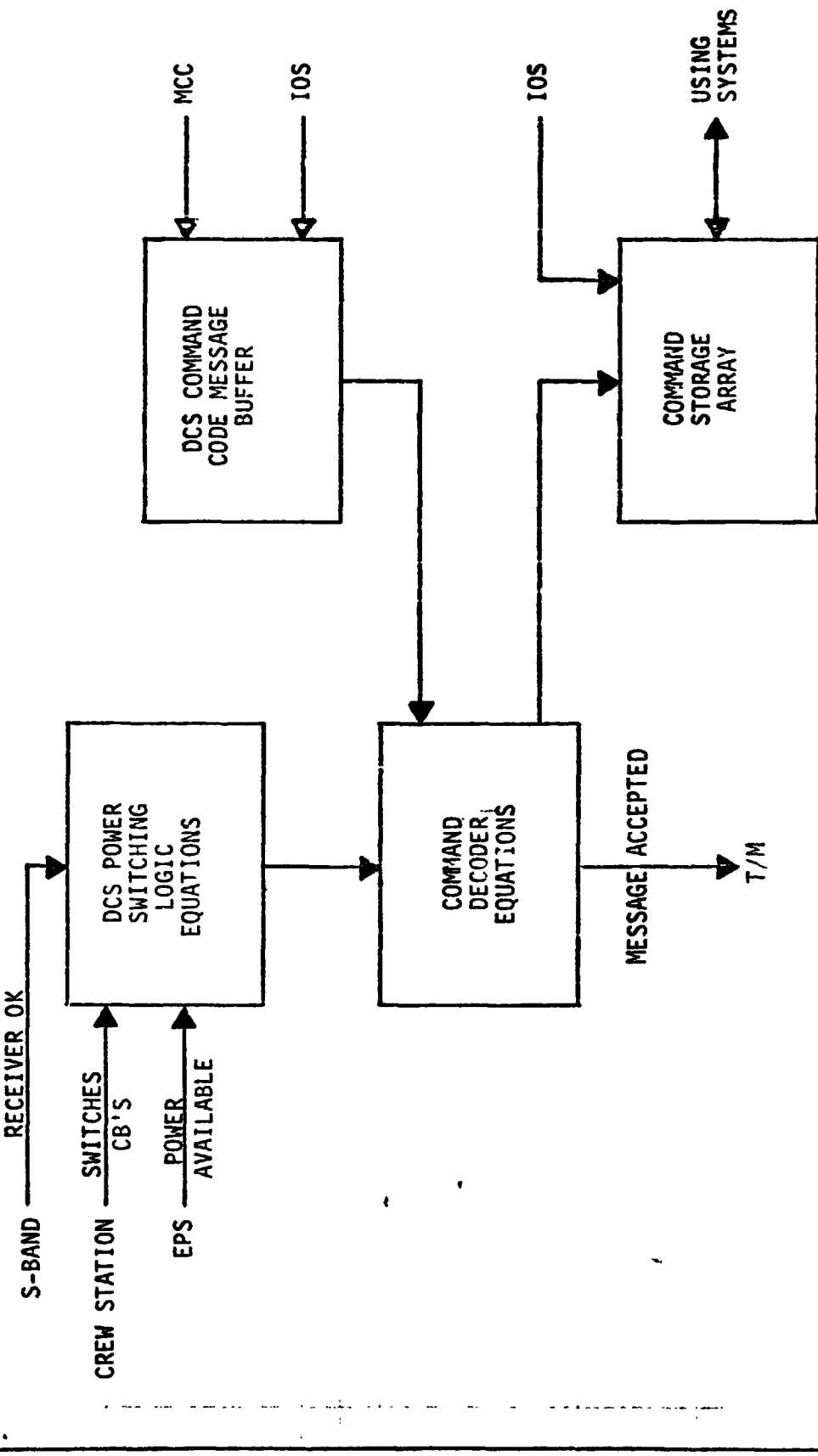
The Up-Link Digital Command Subsystem is simulated by use of software and hardware for the transmission of command data.

In the integrated mode with MCC, an encoded word will be generated by the controller, shipped by hardware telephone equipment to the SMS computer. Within the computer, software will decode the command, set a boolean indicating the command, and generate a boolean for T/M of acceptance of the DCS command.

For the non-integrated mode of computer operation, the instructor will provide up-data commands by manual insertion using the CRT or other means of data entry.

If the advanced training technique of predetermined instructor action is implemented, it will be possible for the remote commands to be established by the computer similar to malfunctions.

The software required is shown in Figure 4.3.4.9. The incoming command word from MCC or the IOS is decoded if the power switching logic equations show that the S-Band receiver has acquired the ground signal in sufficient strength to receive messages, that EPS power is available to the DCS decoder via switches and circuit breakers, and the decoder is operational. The decoder will test the incoming message and store a boolean in the selected command word location and establish a boolean for the T/M program to transmit signifying command message acceptance.



F-398-8-A

4.3.4.9 Digital Command System

4.3.4.10 Television Control Logic Subsystem

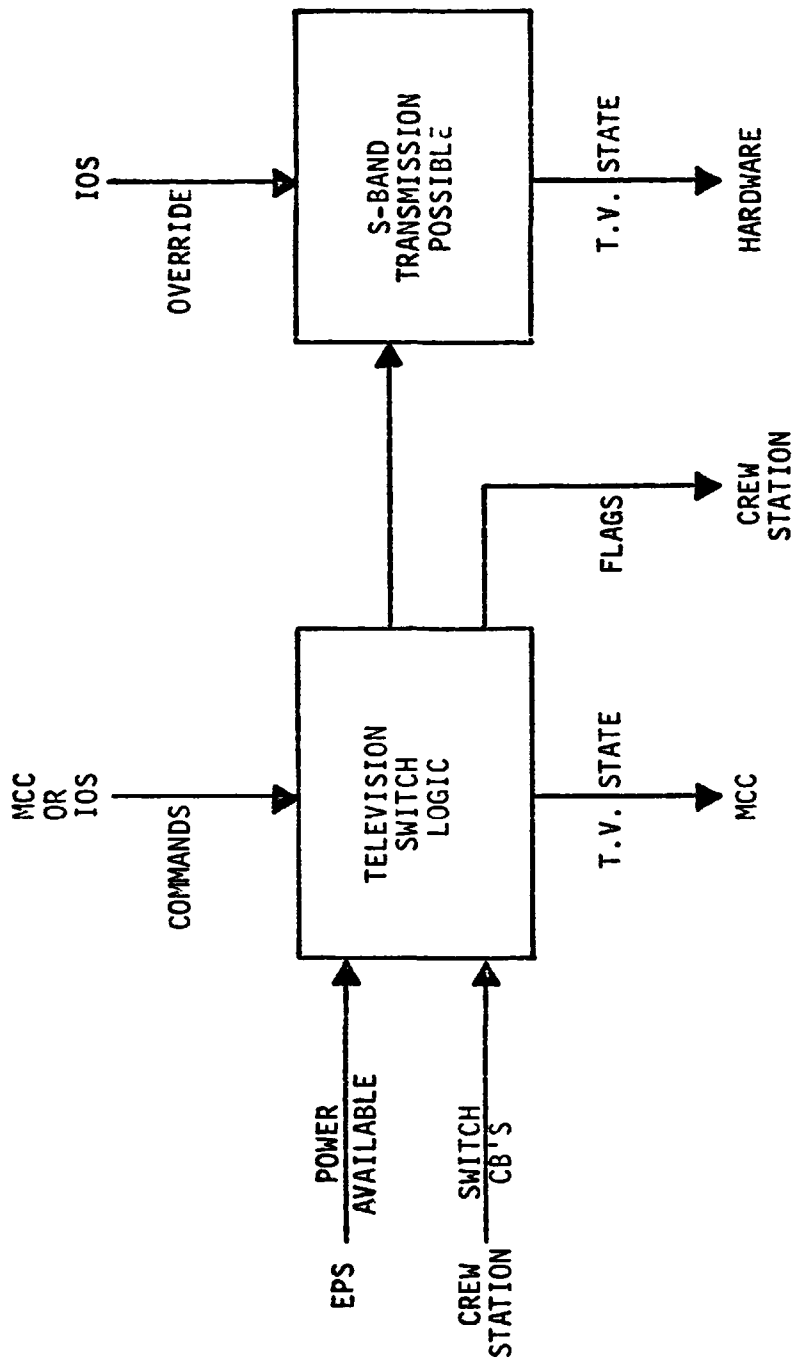
The software simulation of the TV Subsystem will provide the switching and relay logic of the on-board television cameras and monitors. Crew station switch position, circuit breaker position, and remote DCS commands will be included in the equations to determine camera power and receiver power. A test will be made of the S-Band transmitter power level to determine if air-to-ground transmission is possible. A test will also be made on the S-Band received signal to determine if airborne reception is possible.

The IOS will be provided with a remote TV monitor simulating the vehicle monitor or the ground monitor station. Provision shall be made for instructor override over the S-Band signal attenuation and crew station power logic.

4.3.4.11 Recorder Control Logic Subsystem

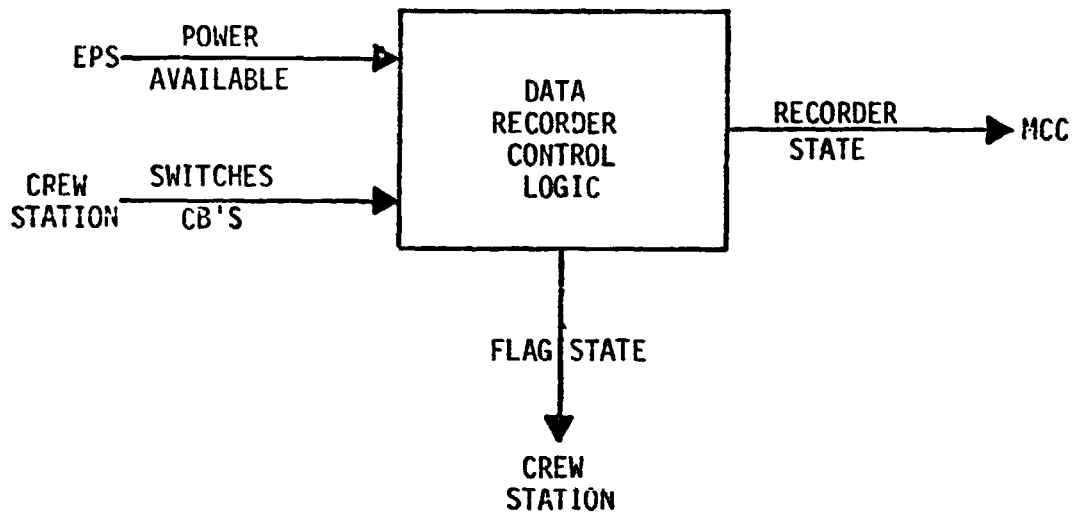
The software simulation of the Voice Recorder will provide the switching and relay logic of the audio recorder. Crew station switch and circuit breaker position will be included in the equations to determine recorder power. Discretes will be provided to determine whether the recorder is in record, rewind, or playback.

The software simulation of the Data Recorder will provide the switching and relay logic of the data recorder unit. Crew station switch and circuit breaker position will be included in the equations to determine recorder power. Discretes will be provided to determine whether the recorder is in record, rewind, or playback.

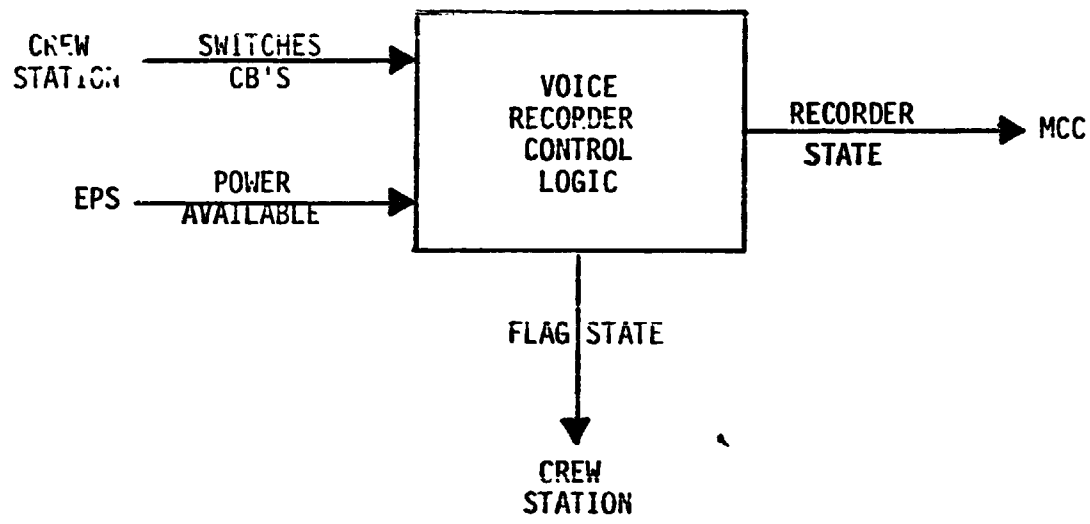


4.3.4.10.-1 TELEVISION CONTROL LOGIC

F.390.8-A



4.3.4.11.-1 Data Recorder Control



4.3.4.11.-2 VOICE RECORDER CONTROL

4.3.4.12 VHF Communication Subsystem

The simulation of the VHF duplex and simplex voice and data communication link will be modeled by calculating the signal strength of the received signal from the ground stations and the transmitted power level out of the vehicle antennas to the ground station. To determine the signal strength, it is necessary to also determine if a station is occulted by the earth and if it is operating on the correct frequency.

The number of possible stations that have line-of-sight coverage is excessive when it is considered that the area of coverage may be as large as the United States. With such coverage, it is necessary to limit the number of ground stations loaded in working core of the computer. At this time, it is felt that twenty-five additional stations, over the normal STDN stations, are sufficient for training. The Reset feature as described in the UHF Logic System will be used.

The process of identifying those stations having line-of-sight, on correct frequency, receiver-transmitter operation, receiver-transmitter signal strength, and signal-to-noise ratio is the same as the UHF Logic System for simulation concept. This process is identified as the signal-to-noise equations in Figure 4.3.12.3.

Following the station-to-vehicle calculations, the equation:

$$\frac{|\vec{r}|^2 - \vec{r}\cdot\vec{r}_{TV}}{|\vec{r} - \vec{r}_{TV}|} < |\vec{r}|^2 - r_E^2$$

where: $\vec{r}$ = Orbiter vector - Earth-centered Inertial

r_{TV} = Target Vehicle vector - Earth-centered Intertial

r_E = Earth radius (assumed spherical model)

solves the problem of line-of-sight from orbiter-to-target vehicle.

The attenuation of the signal paths between the two vehicles will then be calculated based on antenna pattern orientation and vehicle separation distance. The relative bearing angles will be calculated and applied to equations representing the antenna pattern.

Using the attenuation figure for the target vehicle to the shuttle, a boolean will be established for the condition of reception of data of the low 2Kbs rate.

From the attenuation figure for the orbiter to target vehicle, a boolean will be established for the condition of transmission of commands.

Booleans representing the capability to transmit or receive voice will be generated by the programs for use by the audio hardware.

VHF LOGIC SYSTEM

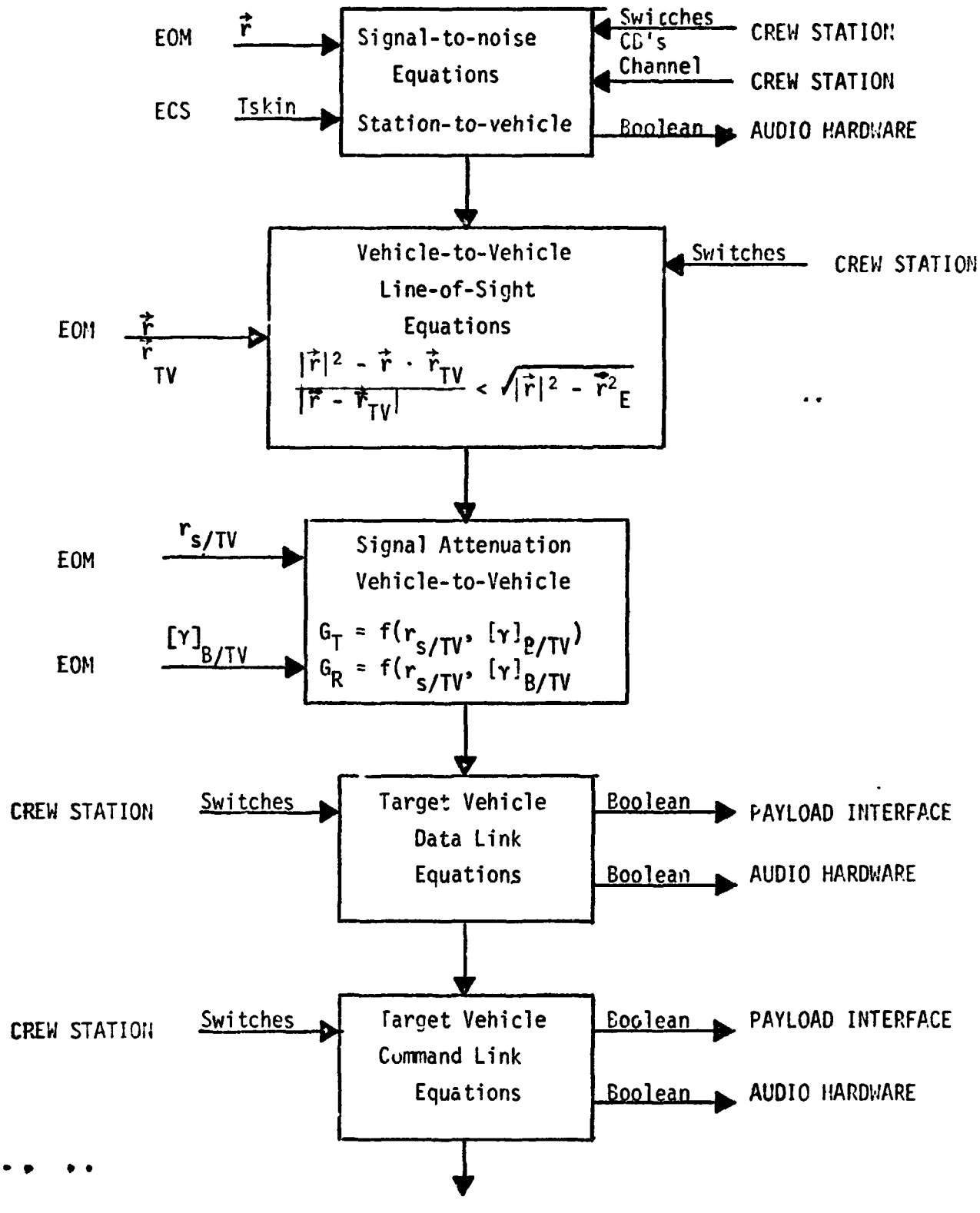
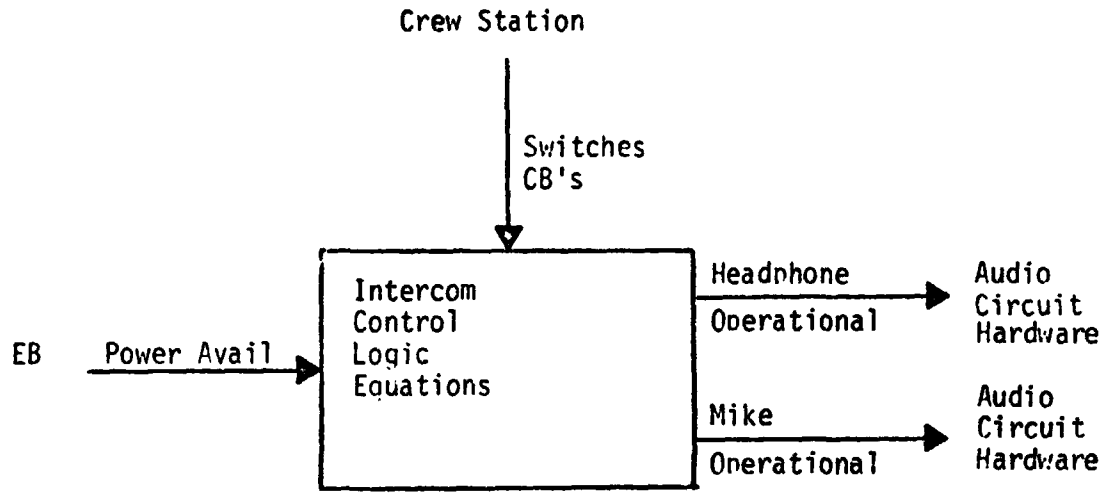


FIGURE 4.3.4.12

4.3.4.13 Intercom Switching Subsystem

The intercom or audio control logic will be simulated for all relay and switching logic by software. Inputs to the logic equations will be provided by the crew station switches and circuit breakers. All real-world electronic relay circuits or logic circuits will be modeled by software equations with malfunctions. Physical control of the voice and noise level on each circuit will be provided by the originating system.

Figure 4.3.4.13 Intercom Control Logic



4.3.4.14 Wide Band Data Link Subsystem

The simulation of the Wide Band transmission of main engine and payload data is not justifiable using existing data lines and equipment. The major problem is that the type of data being transmitted over wide band requires either analog simulation or a very high rate (1,000 samples per second) of digital simulation. There are not enough coax lines to transfer analog data for approximately 50 channels of data. There are coax cables which could transmit 51.2 Kbs of data; however, a digital simulation with an iteration rate of 1,000 cycles per second would be required. This framing rate would require a specially dedicated computer. This method is possible; however, it is felt the cost of this method would prohibit the value derived from transfer of the data to MCC.

Simulation of the measurements (frequency, vibration amplitude, etc) can be transmitted a digital value over the present coax cables with the communication status words. Approximately 20 words would be transmitted at a suggested rate of five times per second. It is felt that redundancy of measurements will make this a realistic exchange between Building 5 and Building 30.

4.3.5 Control and Display

4.3.5.1 Caution and Warning Subsystem

The Caution and Warning Subsystem is suitable for a logic equation simulation. The system is composed of four types of crew cues: alert, caution, warning, and emergency. All four have one common identity - the audio cues. The simulation can be best approached by the division of equations shown in Figure 4.3.5.1.

The Alert power and display logic equations determine if alert power is available, whether the sensors are active, and generates booleans for display in the crew station when input parameters are out of tolerance. A boolean will be generated for cue to the audio device each time a new parameter is sensed out of tolerance.

The Caution and Warning Power equations simulate the separate internal power supplies of Caution power and Warning power. Since these units are controlled by the same switch, circuit breaker, relay functions, they are included together. The equations generate Caution sensor power available and Warning sensor power available booleans to the using subsystem.

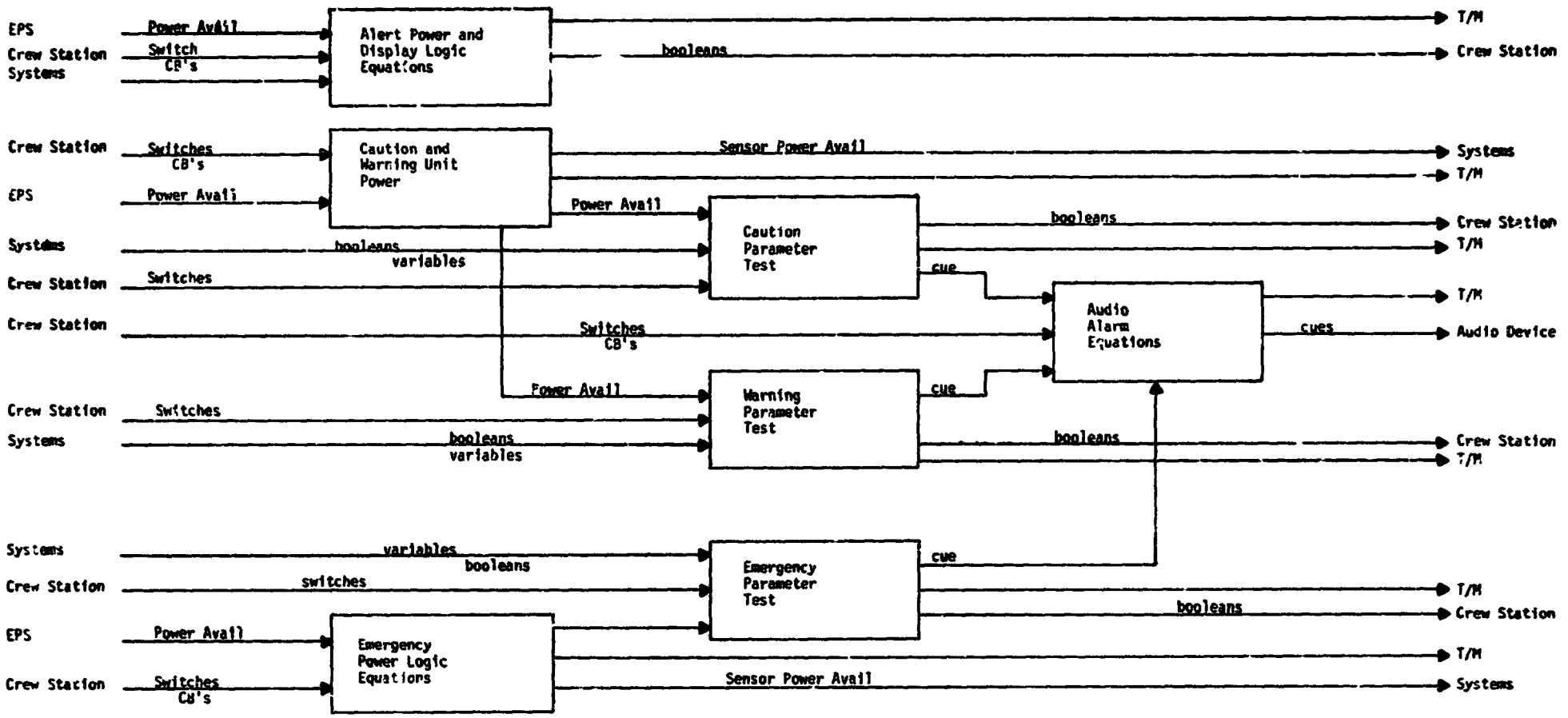
The using subsystems will include the sensor power available term in their equations prior to input to the Caution and Warning System. The inputs are to be tested against stored upper and lower value limit tables in the parameter test equations. Discretes will be generated for each parameter out of tolerance for display in the crew station. In addition a boolean will be generated as a cue to the audio alarm equations each time a new Caution or Warning parameter is found to be out-of-tolerance. Crew station inhibit switches are to be included in the logical test so that discrete alarms can be isolated.

The Emergency power equations simulate the emergency power unit and its control switches and circuit breakers. An emergency sensor power available boolean will be generated by the equations for inclusion in equations of the using subsystems. Inputs for Emergency alarms from the using systems will then be tested against upper and lower limits in the emergency parameter test equations. The test equation will take into account the crew station inhibit switch position.

Booleans generated by the alert, caution, warning, and emergency equations will be included in equations in the audio alarm section to provide cues to the audio devices as to which alarms are on. Volume control of the intercom speakers for the alarms will be a hardware control.

The instrumentation signal conditioning of Caution and Warning Subsystem parameters will be accomplished using sensor and display logic booleans from the Electrical Power Subsystem for crew station display, for reinput to the Caution and Warning Subsystem, or for input to the Telemetry Subsystem Multiplexer Program. The equations of the Caution and Warning Subsystem will be repeated for each unit, either by programmed loops or by repetitive equations, whichever requires the least amount of computer time and core. Required malfunctions for the Caution and Warning simulation are to be designed into the simulation for minimum computer impact.

FIGURE 4.3.5.1 Caution and Warning System



4.3.5.2 Supplementary Display (IOS)

The IOS will be provided with real-time software controlled CRT displays. The following display descriptions are considered as desirable instructor aides, however the design will be highly dependent on the final hardware selection.

For prelaunch a display will be provided for the Ground Support Checkout function. This display will be a functional simulation of the interface performed by GSE equipment and will allow the instructor to monitor the launch vehicle similar to the GSE monitor.

Telemetry displays will be provided by both simulated on-board systems and by the T/M Multiplex program for both integrated and non-integrated training with the Mission Control Center.

A display will be provided to generate a presentation for a Ground Controlled Approach simulation. Because there is no requirement to train GCA controllers or instructors as controliers, the presentation will be in the form of digital correction for the instructor to communicate to the pilot. This would simulate a GCA landing.

An FAA tracking radar coverage could be generated for training pilots in flight pattern in air corridors and flight traffic holding patterns.

A graphic terminal display of the energy management footprint could be generated showing the relative headings of the nearest landing site following a de-orbit, re-entry, or landing approach.

With graphic display capability, simplified flow charts or schematics could be generated to provide the instructor with instant recall for any particular system or component.

System internal data and overall system response displays will be supplied as the by-product of the software engineers' development and system checkout of the simulation. Refer to Section 4.3.7.7.

4.3.5.3 Supplementary Control (IOS)

The IOS will be provided with the capability of controlling the functions normally under GSE control during the simulation of the preflight phase of the vehicle. These control functions will be presented to the instructor by a CRT so that the function is clearly understood and may be easily used.

The function of Mission Control through the Up-Link Command Subsystem will be provided to the instructor by both system function and by coded tabular entry. Provision will be made if possible to avoid having the instructor enter binary coded data for these command functions and to provide binary code insertion for coded command symbols or alpha numerics.

The IOS will be provided with special display/entry page formats so that software data pool may be accessed and modified.

4.3.5.4 Operational Instrumentation Conditioning Subsystem

The power conditioning units, transducer power supplies, and the associated power for signal conditioning of measured and display parameters will be simulated using only dynamic bilevel parameter measurements. These measurements read the nominal value or the minimum value if disabled by malfunctions entered or by loss of power to the unit.

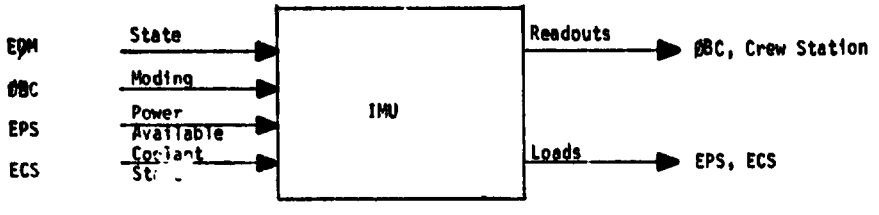
The program will simulate conversion of DC power from the main buses to DC power at voltages required by instrumentation DC power system loads. This simulation will include power supplies such as ± 5, ± 24, ± 28 volt supplies and loads such as display transducers and signal conditioning equipment. All major components such as DC-DC converters, transducers, and signal conditioning equipment will be simulated using Boolean terms representing the state of circuit breakers and switches of the major components.

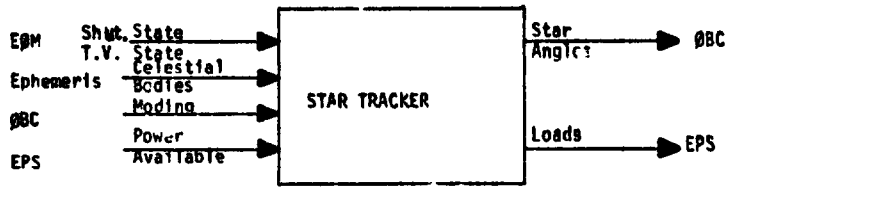
The program will perform the dynamic bilevel calculations of the required supply voltages and equipment operational status. The system will also provide the computed load parameters to the power bus loading subsystem for bus conductance computations and to the ECS sub-system for heat loading. Signal conditioning of parameters for telemetry processing will be simulated by each system checking a Boolean term representing "signal conditioning equipment operational".

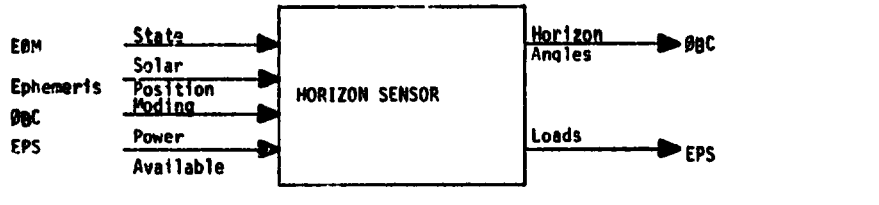
Individual components of the DC-DC converters, transducers, and signal conditioning equipment will not be simulated. Dynamic multilevel parameter calculations will not be necessary since unit input power is not monitored. A converter ON/OFF Boolean will be used to calculate converter temperature since the heat generated by the converter is assumed to be constant when the converter is operational. The overall effect of simulation will be that the unit is either totally operational or completely inoperable.

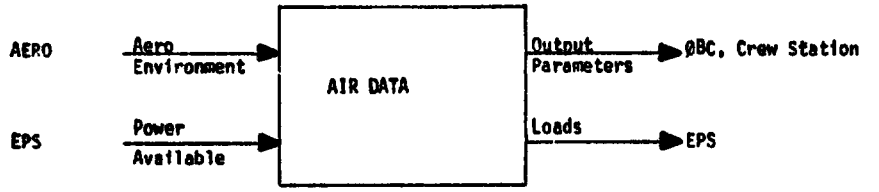
4.3.6 Guidance, Navigation, and Control

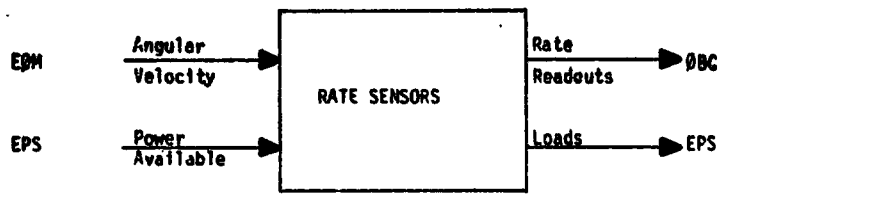
In this section, the conceptual designs for the shuttle vehicle Guidance, Navigation, and Control (GN&C) System are presented, except for the on-board Guidance computers, flight software, and associated interface equipment. The simulation of the on-board computers and their interface equipment is discussed in the Hardware Conceptual Design document. The remainder of the Guidance, Navigation, and Control System comprises navigation and control sensors and thrust vector/aerosurface control subsystems. Sensors discussed below are the Inertial Measurement Unit, Star Tracker, Horizon Sensor, Air Data Computer, body-mounted rate sensors, and body-mounted accelerometers. Other control subsystems considered are the Main Propulsion System Thrust Vector Control, Orbital Maneuvering System Thrust Vector Control, Boost Solid Rocket Motor Thrust Vector Control, and Aerosurface Control. The conceptual design of the generalized target vehicle guidance system is also presented herein. All functions performed by on-board computer flight software are covered in the Hardware Conceptual Design. Since coupling of GN&C subsystems ordinarily takes place through the on-board computer, (e.g., IMU and Star Tracker during platform realignment) they are presented herein as essentially independent subsystems. The configuration of the GN&C simulation is illustrated below:

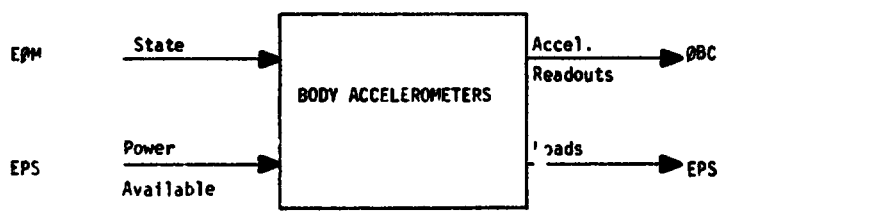

EØM
ØBC
EPS
ECS
State
Moding
Power Available
Coolant St
IMU
Readouts
ØBC, Crew Station
Loads
EPS, ECS

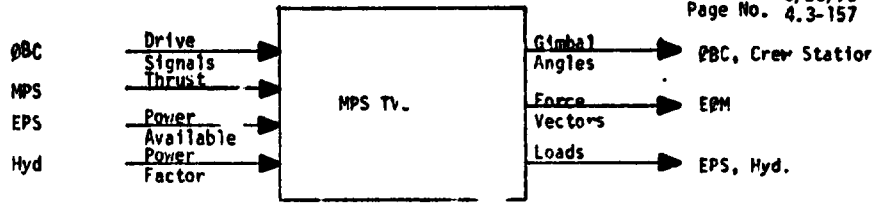

EØM
Ephemeris
ØBC
EPS
Shut, State
T.V. State
Celestial Bodies
Moding
Power Available
STAR TRACKER
Star Angles
ØBC
Loads
EPS

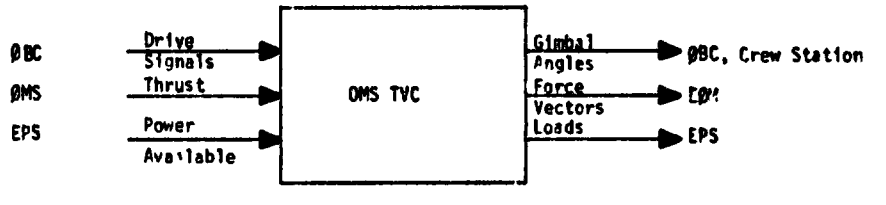

EØM
Ephemeris
ØBC
EPS
State
Solar Position
Moding
Power Available
HORIZON SENSOR
Horizon Angles
ØBC
Loads
EPS

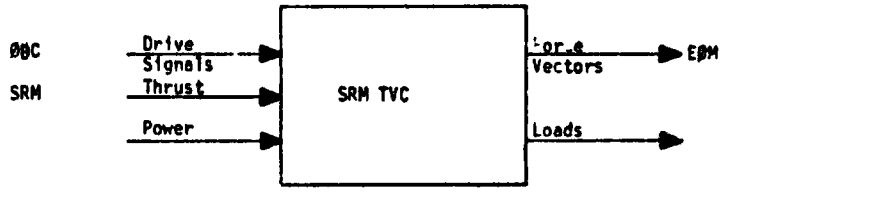

AERO
EPS
Aero Environment
Power Available
AIR DATA
Output Parameters
ØBC, Crew Station
Loads
EPS

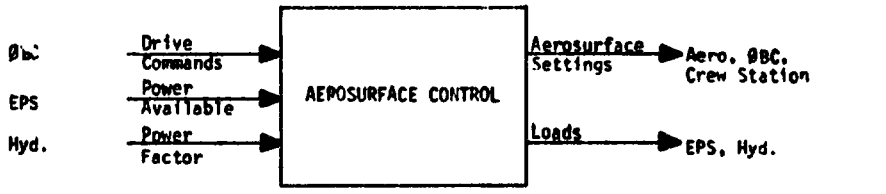

EØM
EPS
Angular Velocity
Power Available
RATE SENSORS
Rate Readouts
ØBC
Loads
EPS

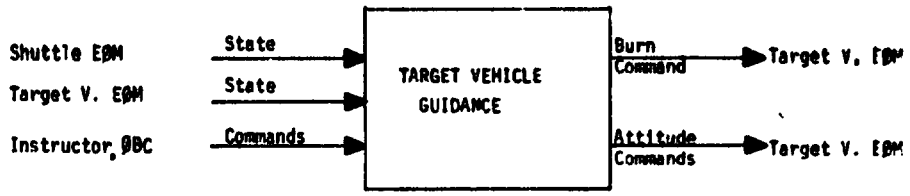

EØM
EPS
State
Power Available
BODY ACCELEROMETERS
Accel. Readouts
ØBC
Loads
EPS


ØBC
MPS
EPS
Hyd
Drive Signals
Thrust
Power Available
Power Factor
MPS TV.
Gimbal Angles
ØBC, Crew Station
Force Vectors
EØM
Loads
EPS, Hyd.


ØBC
ØMS
EPS
Drive Signals
Thrust
Power Available
OMS TVC
Gimbal Angles
ØBC, Crew Station
Force Vectors
EØM
Loads
EPS


ØBC
SRM
Drive Signals
Thrust
Power
SRM TVC
Force Vectors
EØM
Loads


ØBC
EPS
Hyd.
Drive Commands
Power Available
Power Factor
AEROSURFACE CONTROL
Aerosurface Settings
Aero, ØBC, Crew Station
Loads
EPS, Hyd.


Shuttle EØM
Target V. EØM
Instructor, ØBC
State
State
Commands
TARGET VEHICLE GUIDANCE
Burn Command
Target V. EØM
Attitude Commands
Target V. EØM

4.3.6.1 IMU

The IMU simulation will simulate the operation of each of the on-board Inertial Measurement Units. The operation of each of the redundant devices will be simulated independently and simultaneously. It is not currently clear whether the shuttle will use gimballed or strapdown IMUs. A gimballed IMU used on the shuttle vehicle would be a four-gimballed, "all-attitude" device, possessing one redundant gimbal to protect against loss of inertial reference during "gimbal lock". Inputs to a simulation of a gimballed IMU will include vehicle body acceleration (not including gravity - from Translational EOM), vehicle rotational state (Rotational EOM), mode commands, gimbal and gyro torqueing commands (on-board computers), electrical power available, ECS temperature control capacity available, instructor inputs, and crew station switch and circuit breaker status. Outputs from the gimballed IMU simulation will include current gimbal angle resolver outputs, platform accelerometer outputs, power load, heat load, built-in test equipment outputs, and crew station outputs (FDAI, caution and warning, etc.). It is assumed that an IMU thermal control subsystem exists, in order to minimize temperature-related biases to achieve acceptable accuracy. If it exists, it must be functionally simulated. Heat added to the IMU by significant sources will be estimated as a function of electrical power drawn by those sources. Effects of surrounding gas temperature will be included. Heaters, if they exist, will also be simulated in this fashion. Heat transferred to coolant will be calculated as a function of IMU temperature, coolant state and blower state. Thermostatic control of heaters and blowers will be simulated. Power loads due to heater or blower operation will be

provided to the simulated Electrical Power System. IMU temperature will be calculated from heat added to the IMU and heat transferred to the coolant. All IMU operational modes will be simulated, including modes in which the platform stabilization loops are opened. When in cage mode, the platform angles will be returned to null and maintained there. Gimbal torqueing commands (if the capability exists) and power failure effects will be simulated, and the resulting platform orientation with respect to inertial space maintained. When the stabilization loops are closed (normal operation), gyro drifts will be calculated and propagated through the simulation. Drift sources will include free bias and random drift, acceleration sensitive (mass unbalance) drift, and acceleration-squared sensitive (anisoelastic) drift. Dependence of drift properties upon gyro temperatures will be simulated. Acceleration components in gyro input, spin, and output axes will be obtained from the accelerometer simulation in platform axes, and be conditioned by a matrix representing gyro misalignments. Drift properties will be supplied using random numbers, and will exhibit proper standard deviation and autocorrelation when appropriate. The instructor will be given the ability to vary statistical properties, or override randomly varying parameters with constants, for each gyro. Carouselling effects will be included if appropriate. Gyro displacements due to gyro torqueing will be calculated as functions of command and current scale factor (including temperature dependence and other dispersions). Previous spacecraft training simulations have ignored the dynamics of IMU stabilization loops. This has been safe because, at most attitudes, stab loop dynamics were not significantly noticeable to the crew or computer in the three-gimballed platforms used. In the situations wherein stab loop dynamics become noticeable in such platforms, at very high middle gimbal

angles, accurate simulation has been unnecessary. On the Apollo CSM IMU, for example, the stab loops were opened at a middle gimbal angle of 85°. A four-gimballed IMU does not have the same "gimbal lock" problem as the three-gimballed device, but the real-world stab loops do tend to demonstrate interesting (and undesirable) dynamics when the non-redundant middle gimbal angle is at or near 90°, effects called "gimbal flip." Incidentally, with the proper time history of rates, it is possible to obtain "gimbal lock" type effects on a four-gimballed platform, when, for instance, the redundant inner gimbal hits hard stops. It could happen. The exact effects of "gimbal flip" are dependent on such parameters as amplifier gains, motor torques, etc., and can be ameliorated by judicious choices thereof. Moreover, it may be possible during IMU design to find an axis (and stable member alignment) along which vehicle attitude is unlikely to remain long in a 90° offset condition, especially during critical periods. Thus, the "gimbal flip" effects may be fairly unlikely to occur. Balanced against this is the fact that stab loop dynamics are notoriously difficult to simulate in real-time due to high loop gains and, during "gimbal flip," very fast changing trigonometric cross-coupling effects. Sampled-data methods can help, but the problem is a sticky one nevertheless. It is herein assumed that by amplifier adjustment and judicious axis/alignment choice, the "gimbal flip" problem can be reduced well below the point at which simulation thereof is justified for training simulation. Thus, stab loop dynamics are ignored. This conclusion should be reviewed at a later stage in shuttle design. Hence, the transformation matrix from inertial coordinates to the true platform will be calculated directly from the gyro drifts, gyro torqueing angles, carouselling (if any), and the previous value of the matrix. Perfect stab loops are then assumed. The direction cosine matrix from rotational EOM will then be used to obtain the body to platform matrix, from which gimbal angles (properly

quantized) and FDAI drive signals will be obtained. The platform mounted accelerometers will be simulated as operational when power is available and breakers are properly configured. Body accelerations from Translational EOM will be transformed to true platform coordinates (including carouselling, if appropriate). Accelerometer errors modeled will include bias and noise, scale factor error, misalignment, and scale factor non-linearity. Off-nominal temperature effects will be included as appropriate. Correct statistical properties will be exhibited. Instructor control over the accelerometer error model will be similar to his control over the gyro error model. Sensed acceleration will then be quantized for transfer to the on-board computer. If a non-destruct readout, or a destruct readout which nevertheless carries over fractional parts of quanta is used, this feature will be simulated. The conceptual design of the simulation of each gimballed IMU is sketched in Figure 4.3.6.1-1.

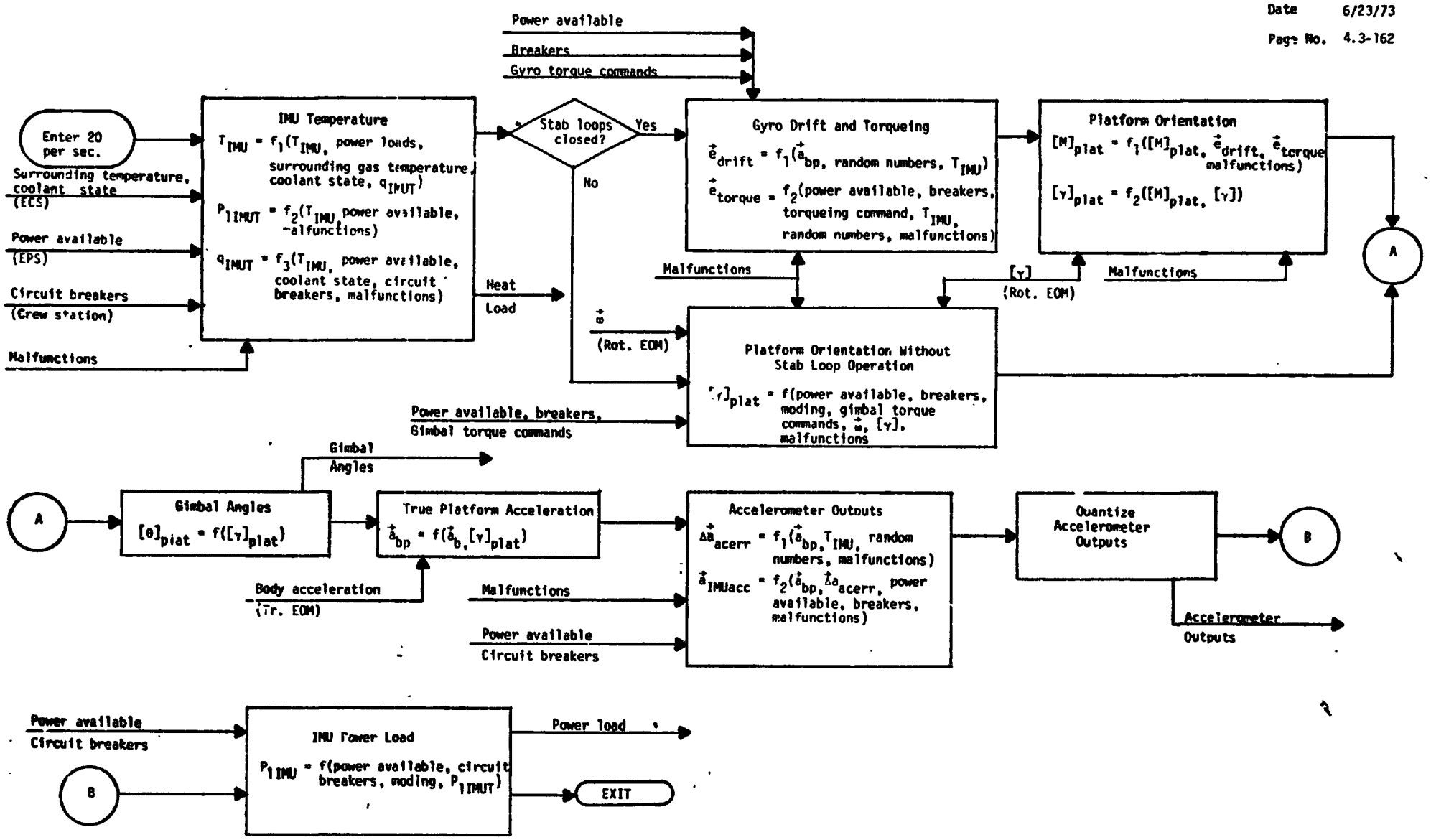


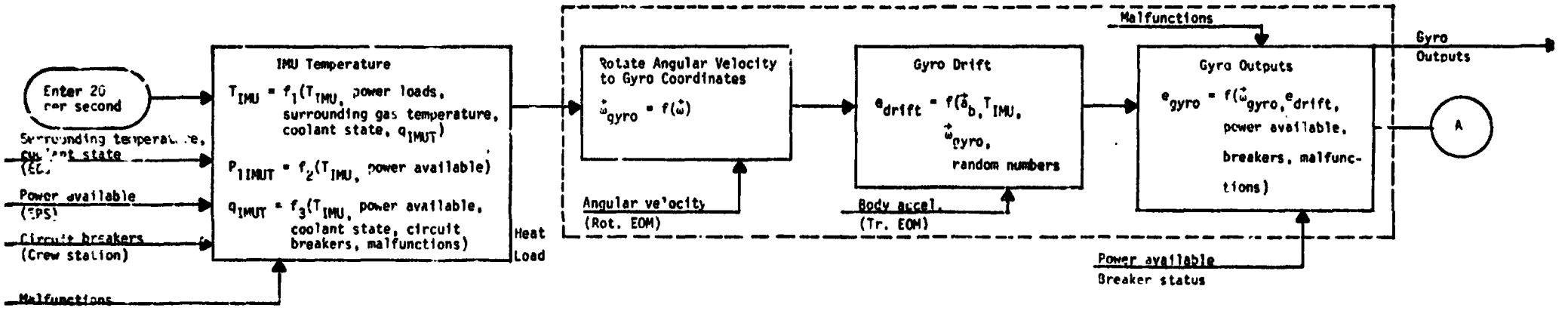
FIGURE 4.3.6.1-1

Symbol Dictionary for Figure 4.3.6.1-1

$\vec{a}_b$	Shuttle body acceleration (without gravity)
$\vec{a}_{bp}$	Shuttle body acceleration in platform coordinates
$\vec{a}_{IMU\,acc}$	IMU actual sensed acceleration
$\vec{e}_{drift}$	IMU gyro drift
$\vec{e}_{torque}$	IMU gyro torqueing angles
$[M]_{plat}$	True platform to inertial transformation
$P_{\rceil IMU}$	IMU power load
$P_{\rceil IMUT}$	IMU temperature control power load
q_{IMUT}	IMU heat lost to coolant
$[\gamma]$	Shuttle attitude direction cosines
$[\gamma]_{plat}$	Platform to body transformation
$\Delta\vec{a}_{acerr}$	Accelerometer error vector
$[\theta]_{plat}$	Indicated gimbal angles
$\vec{\omega}$	Shuttle angular velocity

A strapdown IMU is a device using gyros and accelerometers rigidly connected to the vehicle. The use of redundant triad or dodecahedron instrumentation arrays, mechanization of failure detection, and location of data processing are not clearly defined. A conceptual design of the sensor portion of the strapdown IMU is described in the following sentences, with the assumption that failure detection and measurement processing is handled by the on-board guidance computers. This assumption may be invalid. Inputs to the simulated strapdown IMU will include vehicle body acceleration (not including gravity - from translational EOM), vehicle angular rates (Rotational EOM), electrical power available, ECS temperature control capacity available, instructor inputs, and crew station switch and circuit breaker status. Outputs from the strapdown IMU simulation will include current gyro and accelerometer readouts, power load, heat load, and crew station outputs (caution and warning, etc.). A temperature control system will be simulated, if it exists, in a similar fashion to that described for the gimballed IMU. Current vehicle angular velocity is obtained, and its components in each gyro axis system (input, spin, output) are found. All drift error sources listed for gimballed platform gyros will be included, as well as rate-dependent scale factor errors and rate-squared-dependent scale factor non-linearities. Temperature dependence will be modelled as appropriate. Statistical properties and instructor intervention will be provided as described in the gimballed IMU conceptual design. Resulting gyro outputs, obtained from angular velocity in sensor axes and gyro drift, will be quantized correctly for transmission to the on-board computers. Body accelerations will be rotated to accelerometer coordinates for each device, and the accelerometer error model discussed under gimballed IMU's applied. Sensed accelerations will be quantized correctly for the use of the on-board computers. The strapdown IMU conceptual design is sketched in Figure 4.3.6.1.-2.

PERFORM FOR EACH GYRO


Enter 20 per second
Surrounding temperature, coolant state (EC)
Power available (EPS)
Circuit breakers (Crew station)
Malfunctions
IMU Temperature
$T_{IMU} = f_1(T_{IMU}$, power loads, surrounding gas temperature, coolant state, $q_{IMUT})$
$P_{IIMUT} = f_2(T_{IMU}$, power available)
$q_{IMUT} = f_3(T_{IMU}$, power available, coolant state, circuit breakers, malfunctions)
Heat Load
Rotate Angular Velocity to Gyro Coordinates
$\vec{\omega}_{gyro} = f(\vec{\omega})$
Angular velocity (Rot. EOM)
Gyro Drift
$e_{drift} = f(\vec{a}_b, T_{IMU}, \vec{\omega}_{gyro}$, random numbers
Body accel. (Tr. EOM)
Malfunctions
Gyro Outputs
$e_{gyro} = f(\vec{\omega}_{gyro}, e_{drift}$, power available, breakers, malfunctions)
Power available
Breaker status
Gyro Outputs
A

PERFORM FOR EACH ACCELEROMETER

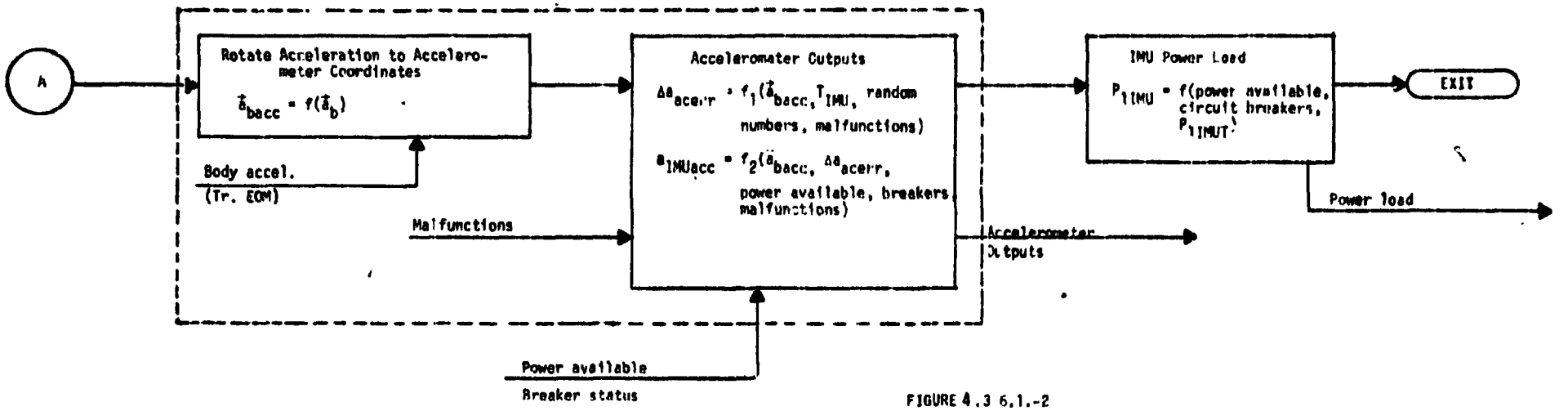


FIGURE 4.3 6.1.-2

Symbol Dictionary for Figure 4.3.6.1.-2.

$\vec{a}_b$	Shuttle body acceleration (without gravity	q_{IMUT}	IMU heat lost to coolant
		Δa_{acerr}	Accelerometer error
$\vec{a}_{bacc}$	Shuttle body acceleration in accelerometer coordinates	Θ_{gyro}	Gyro output
		$\vec{\omega}$	Shuttle angular velocity
a_{IMUacc}	Actual acceleration sensed by accelerometer	$\vec{\omega}_{gyro}$	Shuttle angular velocity in gyro coordinates
e_{drift}	gyro drift		
P_{lIMU}	IMU power load		
P_{lIMUT}	IMU temperature control power load		

Iteration rates of 20 per second are cited for the IMU simulation. These rates correspond to the rotational EOM update rate. On-board computer update rates could force an alteration in IMU iteration, or, alternately, render advisable a high speed, simplified approximation loop which would be corrected at a lower frequency by the more-detailed simulation outlined above. If time is short, the accelerometer readout loop could probably be iterated at a lower rate, perhaps 10 per second.

4.3.6.2 Star Tracker

The Star Tracker simulation will simulate the operation of each of the shuttle vehicle star trackers. The operation of each of the redundant devices will be simulated independently and simultaneously. Detailed design data is not abundant on the device to be used, so a number of assumptions have been made below. Inputs to the star tracker simulation will include star tracker moding commands

(on-board computer), shuttle body attitude (rotational EOM), celestial body positions (ephemeris), vehicle inertial position (translational EOM), power available (EPS), and crew station switch/circuit breaker settings. Outputs will include azimuth and elevation of star or beacon being tracked, device power load, built-in test equipment outputs, and crew station outputs (caution and warning, etc.). It is assumed that the star tracker possesses two basic operational modes, search and track. In search mode, the brightest light source within a small portion of the device field of view centered about a point commanded by the on-board computer will be acquired. If no light source of sufficient magnitude exists in that region, the entire field of view will be scanned and the brightest object acquired. Upon acquisition, the star tracker switches to tracking mode, and tracks the acquired light source, within a very small portion of the field of view. It is also assumed that the computer can place the device in an inactive mode. When a tracker is active, the transformation between tracker boresight coordinates and the inertial reference coordinate system is calculated. Positions of earth, sun, and moon are found in the sensor coordinate system. It is assumed that the presence of the sun, illuminated moon, or illuminated earth in or near the tracker search or track field of view will cause interference. It is further assumed the tracker can detect this interference and will send an error discrete when it occurs. When the entire field of view is occulted by a darkened earth, it is assumed that the tracker will revert to and remain in search mode. If the tracker demonstrates different behavior in those situations, it will be approximately simulated instead. It should be noted that the proposed on-board computer software has logic which will prevent any of these error conditions from occurring except in extreme IMU or computer malfunction cases. Thus, precise

simulation thereof should not be necessary. The tracker should not work normally in case of such severe malfunction, however, so the condition must be detected and its effects approximated. In search mode, a table of star positions and magnitudes will be used to determine which stars are within the field of view. Planets in the field of view will be determined using ephemeris data. Visible target vehicle tracker beacons within the field of view will be noted, using relative position information obtained from shuttle vehicle and target vehicle translational EOM. Target vehicle tracker beacons will be activated by reset terms or instructor input. The brightest object within the applicable portion of the field of view will then be selected. Provision will be made to avoid selecting an occulted object. Brightness of stars and planets will be obtained from reset constants, while target vehicle beacon brightness will be calculated as a function of range. If no object of sufficient brightness is found within the restricted search portion of the field of view, a search of the entire field of view will be similarly simulated. When (and if) a light source is acquired, track mode will be entered. If necessary, entry into track mode will be delayed to simulate finite device search scan time (estimated at 1 second for a search of the total field of view). While the device remains in track mode, the light source will be tracked until it leaves the star tracker field of view, becomes occulted, or enters the interference region of sun, moon, or illuminated earth. If, while tracking a target vehicle beacon, another celestial object which is a more brilliant light source enters the approximate tracking view field, the star tracker will instead continue to track the celestial body. If the tracked object is still being tracked, its azimuth and elevation angle are calculated. Stellar positions used for these calculations will include the effect of abberation.

The position will be obtained in boresight coordinates, from which azimuth and elevation will be calculated, including the effects of sensor misalignment, tracker noise error as a function of apparent magnitude, and scale factor error. Instructor control over statistical properties in the error model will be provided. Output values will be quantized as appropriate. Since the on-board computer contains calculations to ensure that no star is tracked whose apparent direction is that of the earth, refraction due to earth atmospheric effects is not a problem in nominal or near-nominal operation. It could be significant in severe malfunction cases, however. Thus, a simple refraction model will be used on directions of stars whose light passes through a significant level of the earth atmosphere, in order to assure the existence of some dispersion in this case. There is currently no data available on influence of temperature upon device dispersions or the existence of a device temperature control subsystem. Thus, such effects have been omitted. This may have to be altered as further data becomes available. It appears that the on-board computer may interrogate the star tracker angles at any time. Presumably, during star tracker use, body rates would be small--on the order of a 0.1 degree/second. Hence, in 50 milliseconds, motion of 36 arc-seconds could occur. Anticipated star tracker resolution is 30 arc-seconds. As the IMU is updated each 50 milliseconds, it appears that, to obtain reasonable realignment measurement simulation, the star tracker angles must be updated at the same rate. If time is critical, sufficient accuracy could probably be obtained by extrapolation by integrating using body rates directly, and updating at slower intervals with the full program. At this time, however, a 50 millisecond update time is used. The conceptual design for a star tracker is sketched in Figure 4.3.6.2.-1.

SWITCH SETTINGS, BREAKERS, POWER AVAILABLE, MODING, MALFUNCTIONS

ENTER 20 PER SEC

ACTIVE MODE?

YES

NO

(1) INACTIVE STATUS OUTPUTS
$P_{est} = f(\text{POWER AVAILABLE})$

POWER AVAILABLE

EXIT

POWER LOAD

(2) LOCATE CELESTIAL BODIES
$[M]_{st} = f_1([\gamma])$
$\vec{U}_{est} = f_2([M]_{st}, \vec{r})$
$U_{mst} = f_3([M]_{st}, \vec{U}_m)$
$\vec{U}_{sst} = f_4([M]_{st}, \vec{U}_s)$

POSITION (tr, EOM)

ATTITUDE (tr, EOM)

SUN, MOON POS'N (EPHEMERIS)

MODE?

SEARCH

TRACK

COMPUTER COMMANDS

(3) CENTER OF SEARCH AREA
$U_{sc} = f(\text{COMPUTER INPUTS, MALFUNCTIONS})$

INTERFERENCE?

NO

YES

SHUTTLE POS'N (TR EOM)

T.V. POS'N (TV TR. EOM)

$U_{planets}, V_{ces}$ (EPHEMERIS)

INSTRUCTOR INPUTS

(4) POSITION OF TRACKED OBJECT
$U_{trck} = f([M]_{st}, \text{MALFUNCTIONS}, \vec{U}_{planets}, \vec{r}, \vec{r}_{tv}, \text{INST. INPUT}, V_{ces})$

MALFUNCTIONS

D

(5) ERROR RESPONSE
$P_{1st} = \text{CONSTANT}$
SET ERROR FLAG

POWER LOAD

EXIT

C

E

A

SEARCH AREA OCCLUDED?

NO

YES

$\vec{r}$, h (TR, EOM)

$\vec{r}_{tv}$ (TV EOM)

$\vec{U}_{planets}$ (EPHEMERIS)

INSTRUCTOR INPUTS

(6) FIND BRIGHTEST OBJECT IN SEARCH AREA
$\vec{U}_{brite} = f(\vec{U}_{planets}, [M]_{st}, \vec{r}, \vec{r}_{tv}, \text{INSTR. INPUT}, \vec{U}_{est}, h, \vec{U}_{sc})$

IS THERE A BRIGHTEST OBJECT?

NO

YES

INTERFERENCE IN FOV?

NO

YES

$\vec{r}$, h (Tr, EOM)

$\vec{r}_{tv}$ (TV Tr, EOM)

$\vec{U}_{planets}$ (EPHEMERIS)

INSTRUCTOR INPUTS

D

(7) FIND BRIGHTEST OBJECT IN FIELD OF VIEW
$\vec{U}_{brite} = f(\vec{U}_{planets}, [M]_{st}, \vec{r}, \vec{r}_{TV}, \text{INSTR. INPUT}, \vec{U}_{est}, h)$

B

(8) GO TO TRACKING MODE
$P_{1st} = \text{CONSTANT}$

EXIT

POWER LOAD

B

IS THERE A BRIGHTEST OBJECT?

YES

NO

(9) STAY IN SEARCH MODE
$P_{1st} = \text{CONSTANT}$

POWER LOAD

EXIT

C

INTERFERENCE

No

Yes

D

$\vec{r}$, h (TR EOM)

$\vec{r}_{tv}$ (TV Tr, EOM)

$\vec{U}_{planets}$

INSTRUCTOR INPUTS

(10) BRIGHTEST OBJECT IN TRACK SEARCH AREA
$\vec{U}_{brite} = f(\vec{U}_{planets}, [M]_{st}, \vec{r}, \vec{r}_{tv}, \text{INSTR. INPUT}, \vec{U}_{est}, h, \vec{U}_{trck})$

ANY VISIBLE OBJECT?

YES

NO

(11) GO TO SEARCH MODE
$P_{1st} = \text{CONST.}$

EXIT

POWER LOAD

$\vec{U}_{trck} = \vec{U}_{brite}$?

YES

NO

$\vec{U}_{trck} = \vec{U}_{brite}$

MALFUNCTIONS

(12) GIMBAL ANGLES
$\alpha_{st} = f_1(\vec{U}_{trck}, \text{MALFUNCTIONS})$
$\beta_{st} = f_2(\vec{U}_{trck}, \text{MALFUNCTIONS})$
$P_{st} = \text{CONSTANT}$

POWER LOAD

STAR TRACKER GIMBAL ANGLES

EXIT

FIGURE 4.3.6.2-1

Symbol Dictionary for Figure 4.3.6.2-1.

h	Shuttle altitude
$[M]_{ST}$	Inertial to sensor coordinate transformation
P_{1st}	Star tracker power load
$\vec{r}$	Shuttle vehicle position vector
$\vec{r}_{TV}$	Target vehicle position vector
$\vec{U}_{brite}$	Direction of brightest object
$\vec{U}_{est}$	Earth direction, sensor coordinates
$\vec{U}_{m}$	Moon direction, inertial coordinates
$\vec{U}_{mst}$	Moon position, sensor coordinates
$\vec{U}_{Planets}$	Planetary positions, inertial coordinates
$\vec{U}_{s}$	Sun direction, inertial coordinates
$\vec{U}_{sc}$	Center of search area
$\vec{U}_{sst}$	Sun direction, inertial coordinates
$\vec{U}_{trck}$	position of object being tracked, sensor coordinates
V_{ces}	Aberration parameter
$[\gamma]$	Shuttle vehicle attitude direction cosines

4.3.6.3 Rendezvous Radar

The rendezvous radar subsystem will simulate the operation of each of the snuttle vehicle on-board rendezvous radar subsystems in multi-modes. Passive free-flight payloads are detected by "skin" tracking. The target may be enhanced by transponder. The two major orbiter assemblies are the on-board avionics and the deployable assembly. The deployable assembly is stowed inside the payload bay area with jettison capability. The radar is pulse modulated with a maximum range of 32 N. Mi. Two modes will be simulated--search and auto tracking after lock-on. Angular position will be obtained from computation of the antenna angles, angular rate by simulation of rate gyros. Simulation of this type on-board system is not new to flight simulation. Data on the real world subsystem to be used will be required but little problem is foreseen in the simulation. The above description replaces the Horizon Sensors subsystem in the baseline. The Horizon Sensors have been deleted.

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4.3.6.4 Air Data Computer Sensors

The shuttle orbiter air data computer sensors will be simulated throughout its useful altitude range. Inputs to the simulated on-board computer will include pressure altitude, static atmospheric pressure, dynamic pressure, and outside air temperature (shuttle aerodynamics), crew station switch and breaker settings, pilot barometric correction, power available, and instructor inputs (malfunctions, etc.). Outputs will include parameters output from the real-world device to the on-board computers and crew displays (pressure altitude, baro-corrected altitude, altitude rate, computer air speed, true air speed, mach number, total temperature, static temperature, and built-in test indicator outputs), and power load. It is assumed that sensors as inputs to the on-board computer are required to allow the computer to compute parameters similar to that computed in a DC-10 type system. It is assumed that all control functions are performed by the on-board guidance computers. The results will be used for SAS gain scheduling and crew displays. If there are no other uses, a detailed dispersion model is probably unnecessary, especially for temperatures. Requirements for simulation of digital filters are also questionable in this case. It will be assumed herein that filtering effects are not significant. If required, filters will be adjusted, if necessary, to compensate for a change in iteration rate. Pressure inputs (static and total) will be found from the inputs from shuttle aerodynamics. Noise can be added but is probably unnecessary. Outputs which are a function of the pressure terms will then be calculated with the same equations as those used in the real-world device (pressure-altitude, baro-corrected altitude, altitude rate, mach, computed air-speed). Temperature dependent parameters will be calculated directly from the temperature datum from shuttle aerodynamics, as well as

previously calculated air data parameters, by methods analogous to the equations used by the real-world device for an input of sensed total air temperature. A 20 per second update rate is used herein for the simulated air data sensors. However, if the data is used only for the purposes cited herein, and with the assumed accuracy, it would appear that a 10 per second update rate may well be sufficient. The conceptual design for the simulation of an air-data computer is sketched in Figure 4.3.6.4-1.

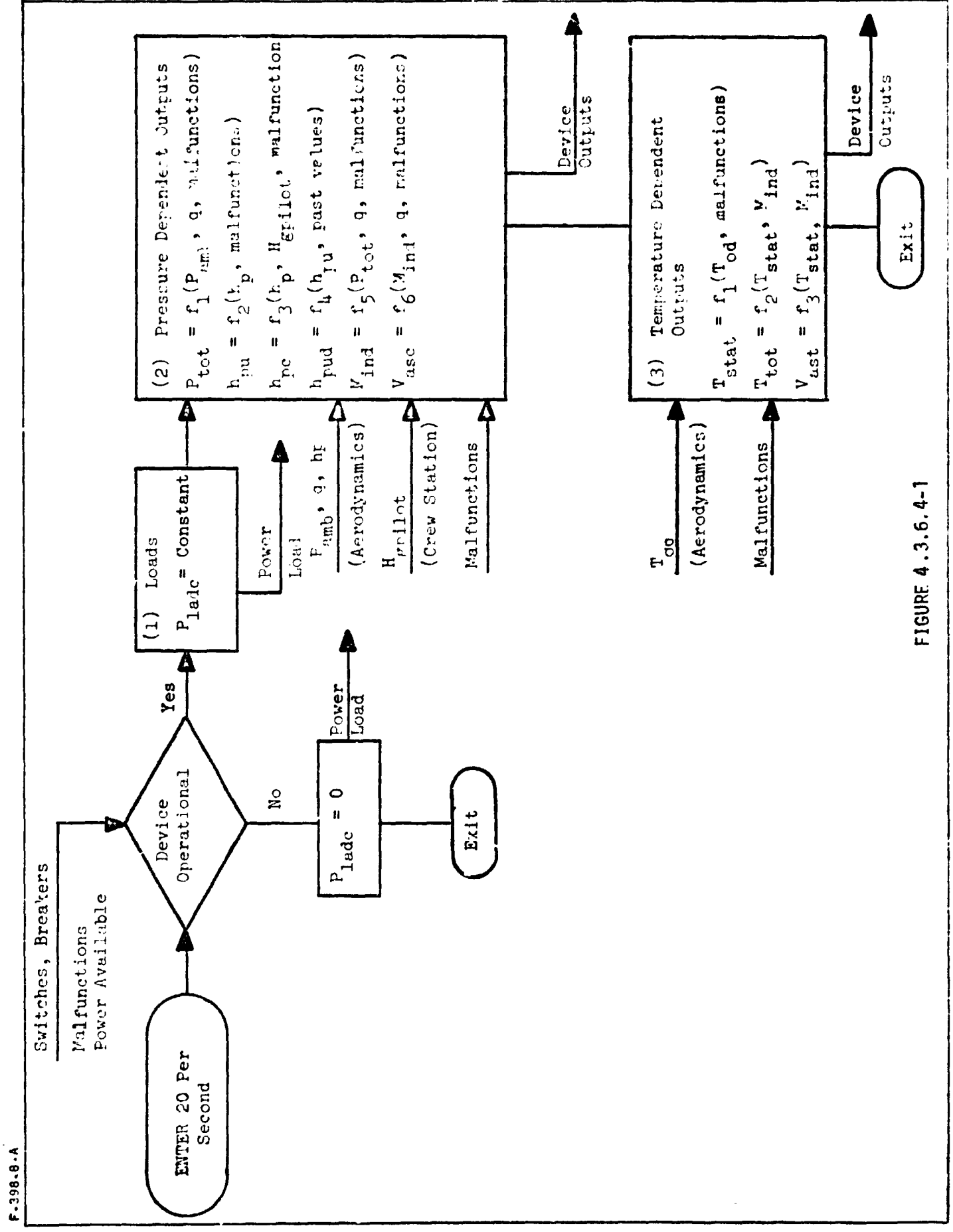


FIGURE 4.3.6.4-1

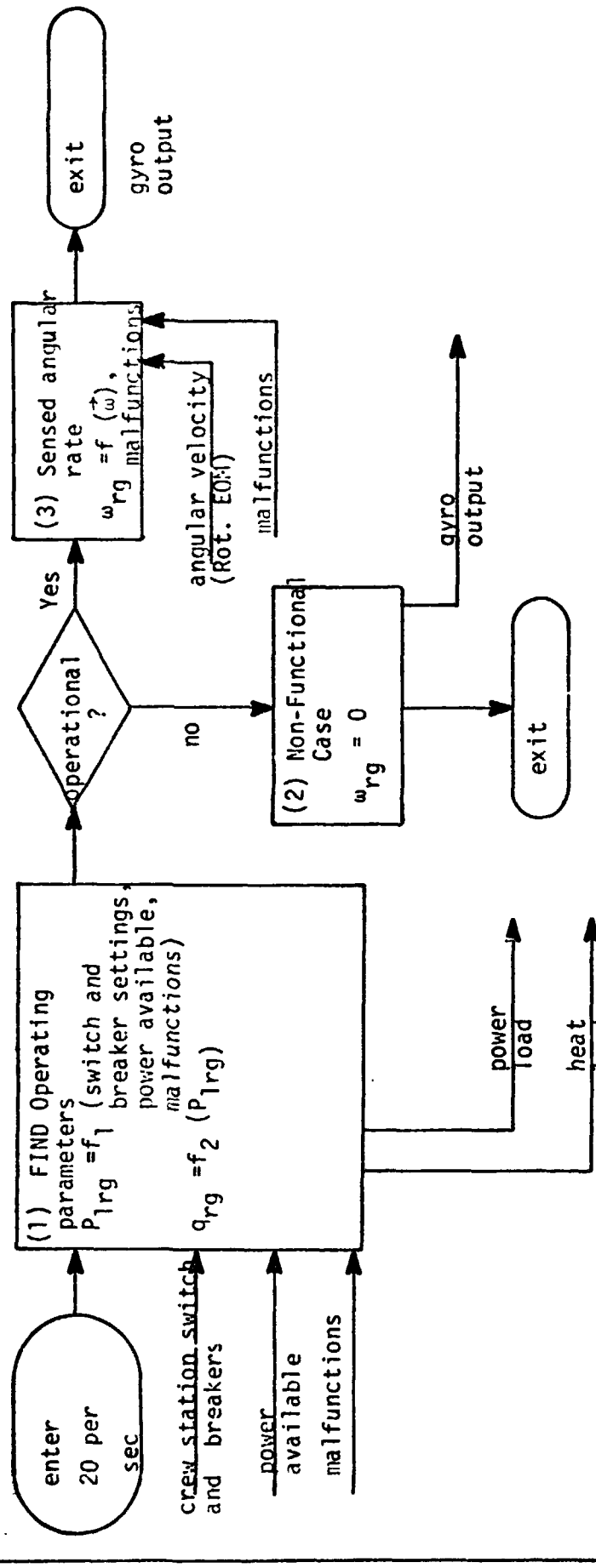
Symbol Dictionary for Figure 4.3.6.4.-1

H_{gpilot}	Pilot-set barometric correction
h_p	Pressure altitude
h_{pc}	Baro-corrected indicated altitude
h_{pu}	Indicated pressure altitude
h_{pud}	Indicated altitude rate
M_{ind}	Indicated mach number
P_{amb}	Ambient atmospheric pressure
P_{ladc}	Power load due to air-data computer
P_{tot}	Total sensed pressure on vehicle
q	Dynamic pressure
T_{oa}	Static air temperature
T_{stat}	Indicated static air temperature
T_{tot}	Indicated total air temperature
V_{asc}	Computed air speed
V_{ast}	Indicated true air speed

4.3.6.5 Rate Sensors

The rate sensor simulation will simulate the operation of each of the vehicle rate gyros (excepting gyros which comprise a part of the primary IMU's) which form a part of the shuttle orbiter. Each rate sensor's operation will be simulated independently and simultaneously in simulated real-time. It is assumed that, in the latest known shuttle real-world GN&C configuration, these rate sensors serve only to provide rate feedback in the vehicle control loop, similar to the Saturn body-mounted rate gyros. Thus, even 3σ drifts, scale factor errors, etc., are unlikely to have any significant effect on vehicle dynamics, since resulting false rates will be tiny compared with vehicle rates, and will not propagate in navigation. If these gyros are instead (or in addition) used in a backup strapdown navigation system, the comments pertaining to error models, etc., for gyros used in strapdown IMU's (section 4.3.6.1) will apply here as well.

Inputs to the rate gyro simulation will include vehicle angular velocity, crew station switch and breaker configuration, power availability, and instructor inputs. Outputs from each simulated rate gyro will include sensed angular velocity, power load, and thermal output. The component of angular velocity (from the rotational equations of motion) along the gyro axis will be calculated. This value will, after quantization and any other required output processing, be used as the device output, providing switches and breakers are properly configured and power is available. Since the equations of motion are updated once each 50 milliseconds, a similar update rate is specified for the body-mounted rate gyros. This interval can be increased if digital control system update is slower, and may have to be decreased if it is faster. The conceptual design of the simulation of a rate sensor is sketched in Figure 4.3.6.5.-1.



F.398-8-A

FIGURE 4.3.6.5-1

Symbol Dictionary for Figure 4.3.6.5.-1

P_{lrg}	rate gyro power load	$\vec{\omega}$	shuttle angular velocity
q_{rg}	rate gyro heat generated	ω_{rg}	body rate sensed by rate gyro

4.3.6.6 Body Accelerometers

The body-mounted accelerometers simulation will simulate the operation of each of the body-mounted accelerometers (excepting those accelerometers which comprise a part of primary Strapdown IMU's) which form a part of the shuttle orbiter. The operation of each body-mounted accelerometer will be simulated independently and simultaneously in simulated real-time. It is assumed that, in the latest shuttle real-world GN&C configuration, these accelerometers serve only to provide load relief inputs in the vehicle control loop, in a similar fashion to the Saturn 1B body-mounted accelerometers. Thus, even 3σ biases, scale factor errors, etc., will probably be sufficiently small as to have no noticeable effect on vehicle control, and will not affect vehicle navigation. If these accelerometers are instead (or in addition) used in a backup strapdown navigation system, the comments pertaining to error models, etc., for accelerometers used in Strapdown IMU's (section 4.3.6.1) will apply here as well. Inputs to the accelerometer simulation will include body accelerations, crew station switch and circuit breaker configuration, power available, and instructor inputs. Outputs from each simulated body-mounted accelerometer will include sensed acceleration, power load, and thermal output. The component of body acceleration (from translational equations of motion) along the accelerometer axis will be calculated. If the device

is located sufficiently far from the vehicle mass center for significant accelerations to result from vehicle angular rates or accelerations, these accelerations will also be included. (This would require vehicle c.g. position, angular rate, and angular acceleration to be added as input parameters.) The resulting output value will, after quantization and any other required output processing, be used as the device output, providing switches and breakers are properly configured and power is available. Since the equations of motion are updated each 50 milliseconds, a similar update rate is specified for the simulated accelerometers. This interval can be increased if digital control system update is slower, and may have to be decreased if it is faster. The conceptual design of the simulation for a body-mounted accelerometer is sketched in Figure 4.3.6.6.-1.

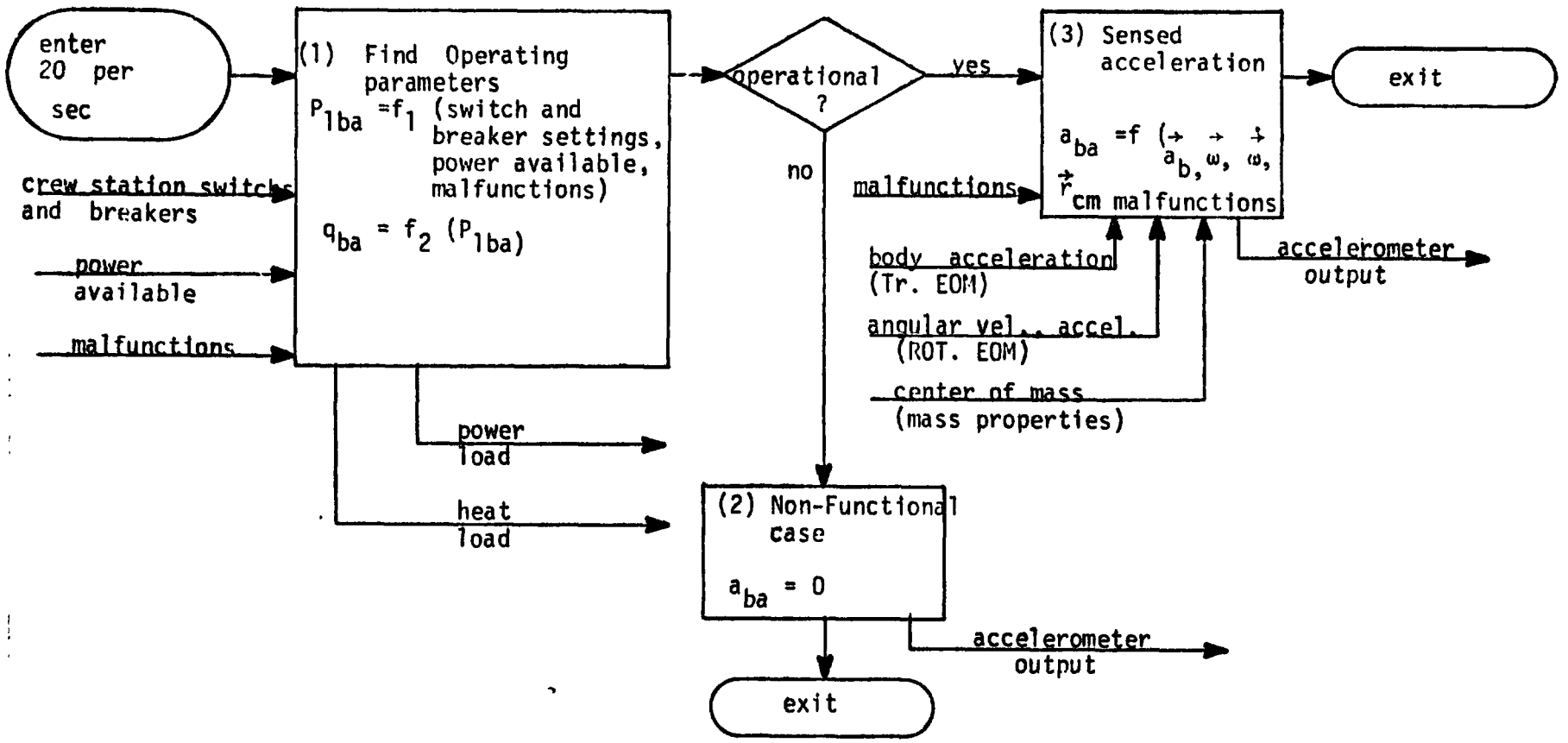


FIGURE 4.3.6.6-1

Symbol Dictionary for Figure 4.3.6.6.-1

$\vec{a}_b$	shuttle body acceleration	q_{ba}	heat generated by body-mounted accelerometer
a_{ba}	acceleration sensed by body-mounted accelerometer	$\vec{\omega}$	shuttle angular velocity
p_{lba}	body-mounted accelerometer power load	$\dot{\vec{\omega}}$	shuttle angular acceleration

4.3.6.7 MPS Thrust Vector Control

The Thrust Vector Control system for each of the three shuttle Main Propulsion System engines will be simulated. Each of the three MPS engines TVC systems will be simulated simultaneously and independnetly, during the times at which the MPS TVC system is in operation. Inputs to the TVC simulation include TVC drive signals through each of the input channels (from the on-board computers), main engine thrust (from the simulated MPS), electrical power available, hydraulic power factors for each hydraulic system, crew station switch and breaker configuration, and instructor inputs. Outputs from the TVC simulation will include gimbal positions, engine force vectors (shuttle body coordinates), electrical power load, hydraulic flows, and status outputs. The MPS TVC will exhibit considerable redundancy, with multiple command signal input channels for each actuator, multiple hydraulic pressure sources for each actuator, and multiple actuators for each gimbal motion direction. Failed channels are disconnected in the case of single channel failure. Actuators are mechanized to drive to null upon certain multiple failures (e.g., loss of two of the four APU-driven hydraulic systems). The operation of the actuator redundancy management systems will be simulated and will respond properly to failures. Failure discretes, hydraulic pressure monitor

outputs, etc., generated by the TVC drivers and monitors will be simulated and output from the TVC simulation. Actuator dynamics in each gimbal degree of freedom will be simulated as a function of input commands, failure detection status, hydrualic power factors in each hydraulic system, and malfunctions. Other effects, such as engine bell damping, will be simulated if significant. Gimbal rate and position limits, and other limits internal to the TVC, will be simulated. After gimbal positions are calculated, each engine's thrust magnitude will be resolved through the calculated gimbal angles to obtain the engine force vector. CMS SPS TVC was iterated at a 50 millisecond rate to approximate proper engine response. While further study when data becomes available may indicate that it is possible by use of sampled-data techniques to lower this rate, a similar rate is currently specified for shuttle to assure accurate closed-loop response. The conceptual design for the simulation of the TVC system for a main engine is sketched in Figure 4.3.6.7.-1.

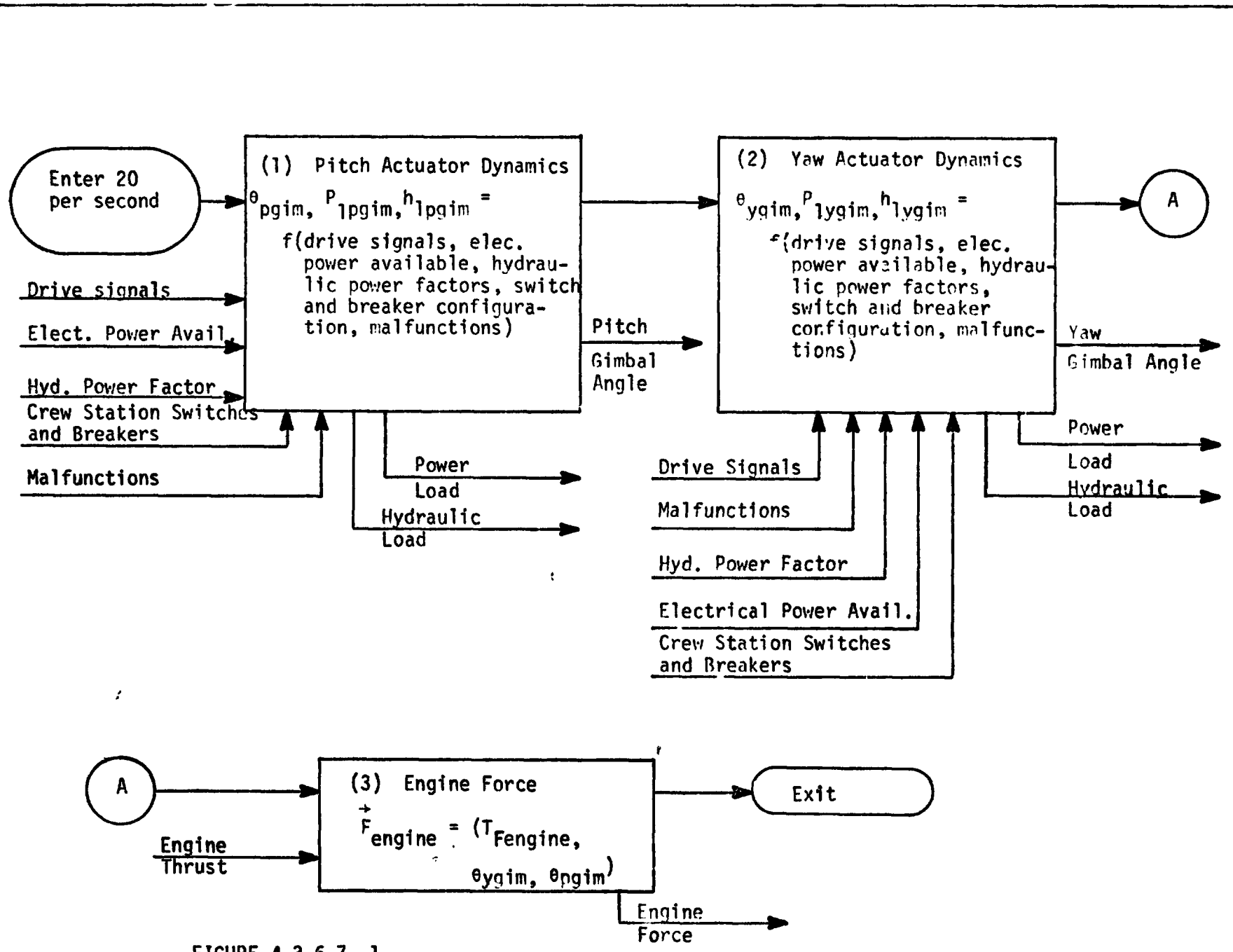


FIGURE 4.3.6.7.-1

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Symbol Dictionary For Figure 4.3.6.7.-1

F_{engine}	engine force vector in shuttle body coordinates
h_{Lpgim}	pitch gimbal actuator hydraulic load
h_{Lygim}	yaw gimbal actuator hydraulic load
P_{lpgim}	pitch gimbal actuator power load
P_{lygim}	yaw gimbal actuator power load
$T_{Fengine}$	engine thrust
θ_{pgim}	engine pitch gimbal angle
θ_{ygim}	engine yaw gimbal angle

4.3.6.8 • <u>OMS Thrust Vector Control</u>

The Thrust Vector Control system for each of the two Orbital Maneuvering system engines will be simulated. Each of the two ØMS engines' TVC systems will be simulated simultaneously and independently, during the times at which the ØMS TVC system is in operation. Inputs to the TVC simulation include TVC drive signals (from on-board computers), ØMS engine thrust (from simulated ØMS), electrical power available, crew station switch and breaker configuration, and instructor inputs. TVC simulation outputs will include gimbal positions, engine force vectors (shuttle body coordinates), electrical power loads, and status outputs. It appears that the ØMS TVC is an electrical-mechanical system, with no hydraulic components, somewhat similar to the Apollo SPS TVC. The actuator dynamics of the Apollo system are significant, especially in malfunction cases. Thus, lags, overshoots, finite rise times, etc., of the actuators will be simulated. There appears to be considerable redundancy in the system, with multiple command signal

input channels. Operation of system redundancy management will be simulated, and any resulting failure discretes will be generated. Actuator outputs in each gimbal degree of freedom will be simulated as a function of input commands, filure detection status and malfunctions. Gimbal rate and position limits, and other limits internal to the TVC, will be simulated. Effects such as engine bell damping will be simulated if significant. After gimbal positions are calculated, each engine's thrust magnitude will be resolved through the calculated gimbal angles to obtain the engine force vector. CMS SPS TVC was iterated at a 20 per second rate to approximate proper engine response. Further study when data becomes available may indicate that it is possible by use of sampled-data techniques to lower this rate. However, a 50 millisecond update rate is currently specified for shuttle to assure accurate closed-loop control response. The conceptual design for the simulation of the TVC system for an ØMS engine is sketched in Figure 4.3.6.8.-1.

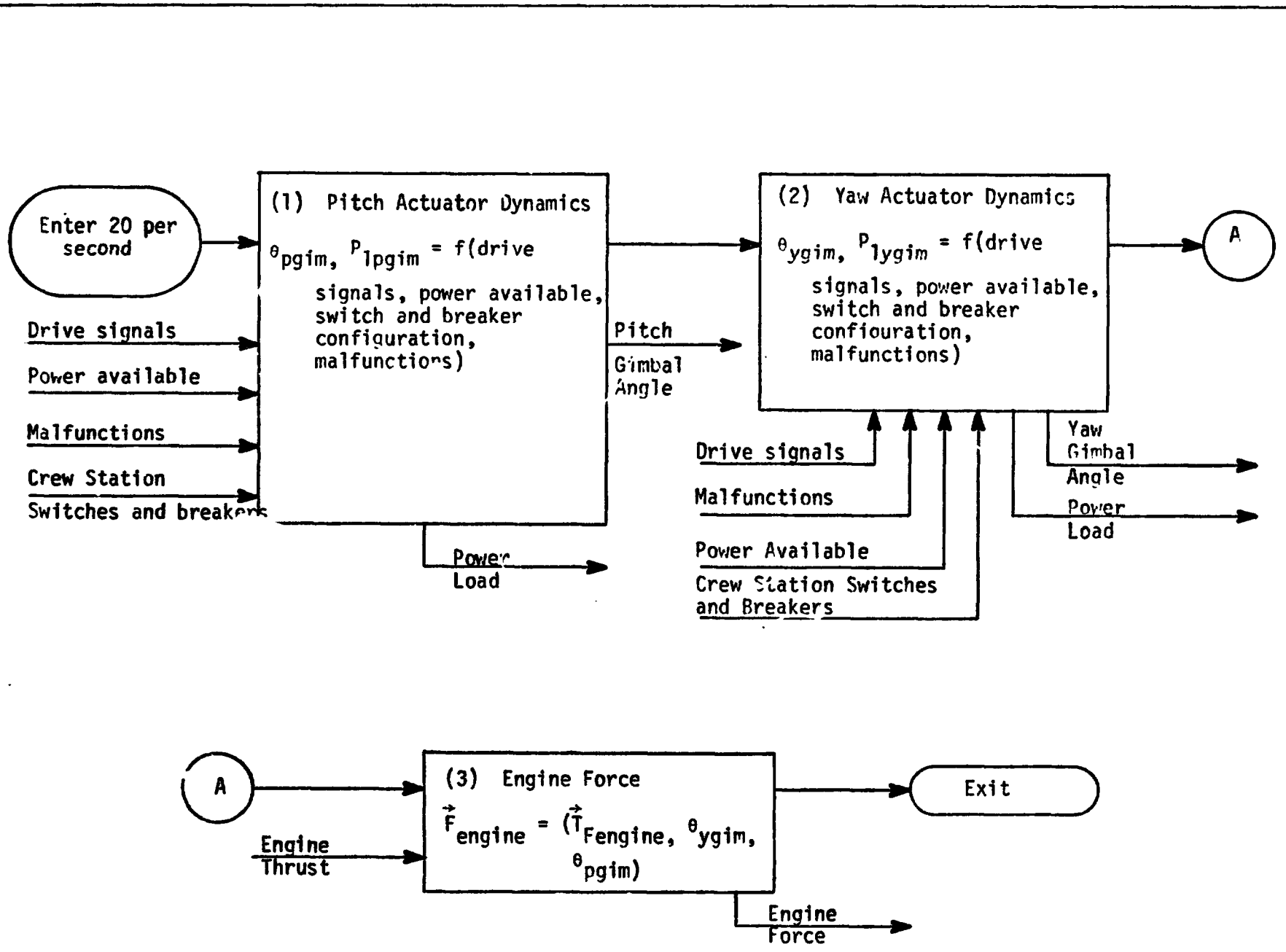

FIGURE 4.3.6.8.-1

Symbol Dictionary for Figure 4.3.6.8.-1

F_{engine}	engine force vector in shuttle body coordinates
P_{lpgim}	pitch gimbal actuator power load
P_{lygim}	yaw gimbal actuator power load
$T_{Fengine}$	engine thrust
θ_{pgim}	engine pitch gimbal angle
θ_{ygim}	engine yaw gimbal angle

4.3.6.9 Boost SRM Thrust Vector Control

The thrust vector control system for each of the two solid rocket booster engines will be simulated simultaneously and independently during the times at which the Boost SRM's are in operation. The method to be used for controlling the SRM thrust vectors is not currently known. For purposes of computer sizing, it will be assumed that the SRM TVC Simulation problem is similar to that for MPS TVC, even though it is not known if SRM engines will be gimballed, or what the power source to be used will be. Inputs to the simulation will include TVC commands and SRM thrust, and outputs will include the force vector from each SRM.

4.3.6.10 Aerosurface Control

The aerosurface control subsystem for each elevon, the vertical stabilizer (rudder/speed brake) and body flap will be simulated. Each of the aerosurface control subsystems will be simulated simultaneously and independently when in operation. Inputs to the aerosurface control system include aerosurface setting commands through each of the input channels for elevon, rudder, and speed brake (from on-board computer), electrical

power available (from Electrical Power Subsystem), hydraulic power factors for each hydraulic system (from Hydraulic Subsystem), crew station switch and breaker configuration, and instructor inputs. Outputs from the aerosurface control system will include elevon and differential elevon settings, rudder setting, speed brake setting, electrical power load, hydraulic flows, and status outputs. Aerosurface control will exhibit considerable redundancy, with multiple command signal input channels for the primary control servos, multiple hydraulic pressure sources for each surface hydraulic actuator, and multiple actuators for each surface. Failed channels are disconnected in the case of single channel failure. Operation of the failure detection and redundancy management provisions will be similated and will respond properly to failures. Failure discretes, hydraulic pressure monitor outputs, etc., generated by the aerosurface control subsystem, will be simulated and output from the simulation. The summing of rudder and speed brake commands to obtain commands for the split vertical stabilizer surface will be simulated to obtain the appropriate surface hydraulic actuator inputs. Actuator dynamics for each surface will be simulated as a function of input commands, failure detection status, hydraulic power factors in each hydraulic system, and malfunctions. Other effects, such as hinge-moments, will be simulated if significant. Rate and position limits of the aerosurface, as well as other limits internal to the subsystem, will be simulated. Previous Singer experience in simulation of high L/D re-entry vehicles has indicated that an update rate of the order of 50 milliseconds for aerosurface simulation is required to maintain proper vehicle response. The conceptual design for the simulation of the aerosurface control subsystem is sketched in Figure 4.3.6.10.-1.

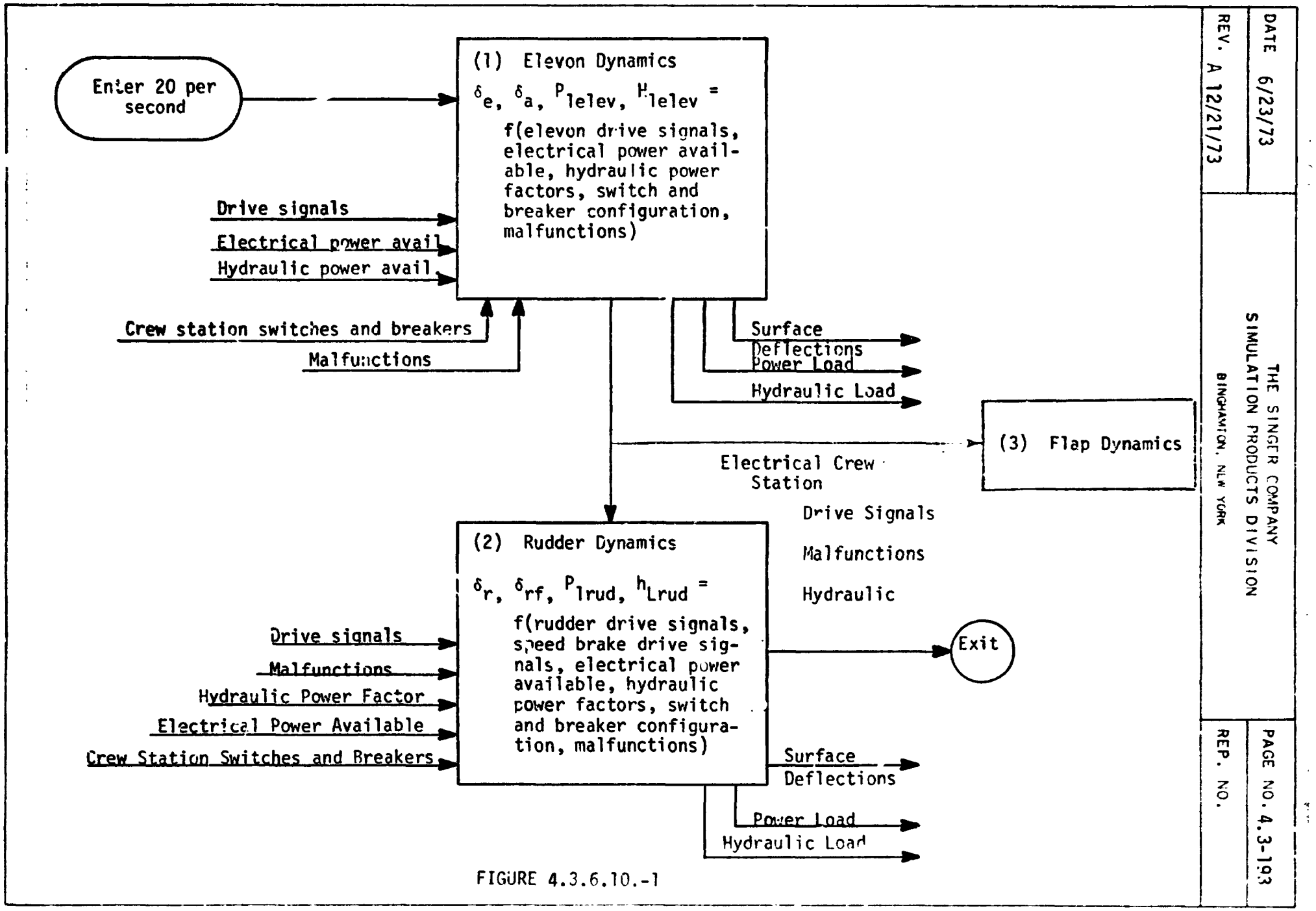

FIGURE 4.3.6.10.-1

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Symbol Dictionary for Figure 4.3.6.10.-1

h_{Lelev}	elevon actuators' hydraulic load
h_{Lrud}	rudder actuators' hydraulic load
P_{lelev}	elevon electrical power load
P_{lrud}	rudder electrical power load
δ_a	ailevon (differential elevon) deflection
δ_e	elevon deflection
δ_r	rudder deflection
δ_{rf}	rudder flare

4.3.6.11 Target Vehicle Guidance and Control

A functional target vehicle guidance system will be simulated for target vehicles. The guidance system will consist of a major loop which performs burn targetting and runs in interruptible time, and a minor loop which feeds attitude commands to the generalized target vehicle control system, and firing commands to the generalized target vehicle propulsion system. A reset boolean will be provided to bypass generalized target vehicle guidance entirely, and another provided to bypass the major loop only, for use in the case that more detailed guidance schemes for particular vehicles are added following simulator delivery. The minor loop guidance system will accept thrusting and attitude commands from either

instructor input

command from shuttle vehicle

guidance major loop/prestored commands

in that order of priority. Instructor input may take the form of direct command, or initiation of prestored commands. Shuttle vehicle commands will be honored only when a reset boolean is set indicating that this target vehicle possesses the capability to accept commands from the shuttle vehicle. Prestored commands may be used either in place of the major loop burn targetting, or merely to specify attitude following the final burn. Prestored commands will be stored as functions of time. Attidue commands (instructor/shuttle vehicle originating/ prestored) may be given in terms of either inertial Euler angles or local horizontal angles, or inertial hold of a local horizontal orientation at the initial point in time. Burn targetting will be provided to the minor loop by specifying ignition time, burn duration, and inertial burn attitude (inertial

Euler angles or inertial hold of a local horizontal orientation). The minor loop will process this information and provide inertial attitude commands for the generalized target vehicle control, and engine ignition and cutoff times to generalized target vehicle propulsion. The major loop will calculate burn targetting assuming a coelliptic rendezvous sequence of three burns (NCC, NSR, TPI). The coelliptic sequence could be expanded to later include preliminary phasing burns, if necessary. Targetting presettings will be instructor-changeable, and targetting for a given burn can be recycled by instructor command. Targetting data (ignition time, burn duration, total ΔV, attitude) will be available for instructor display. Provision will be made to inhibit TPI targetting if the shuttle vehicle will perform this burn. Burn targettings will be performed immediately following the preceding burn's conclusion, and re-preformed about 10 minutes before estimated burn time. Target vehicle major loop guidance will be able to share interruptible time, and a number of (interruptible) targetting subroutines, with instructor aids targetting (described in Section 4.3.7.6). An iteration rate of 10 per second is specified for target vehicle loop guidance, matching the update rate of target vehicle rotational EOM. The conceptual design for target vehicle guidance and control is sketched in Figures 4.3.6.11.-1 and 4.3.6.11.-2.

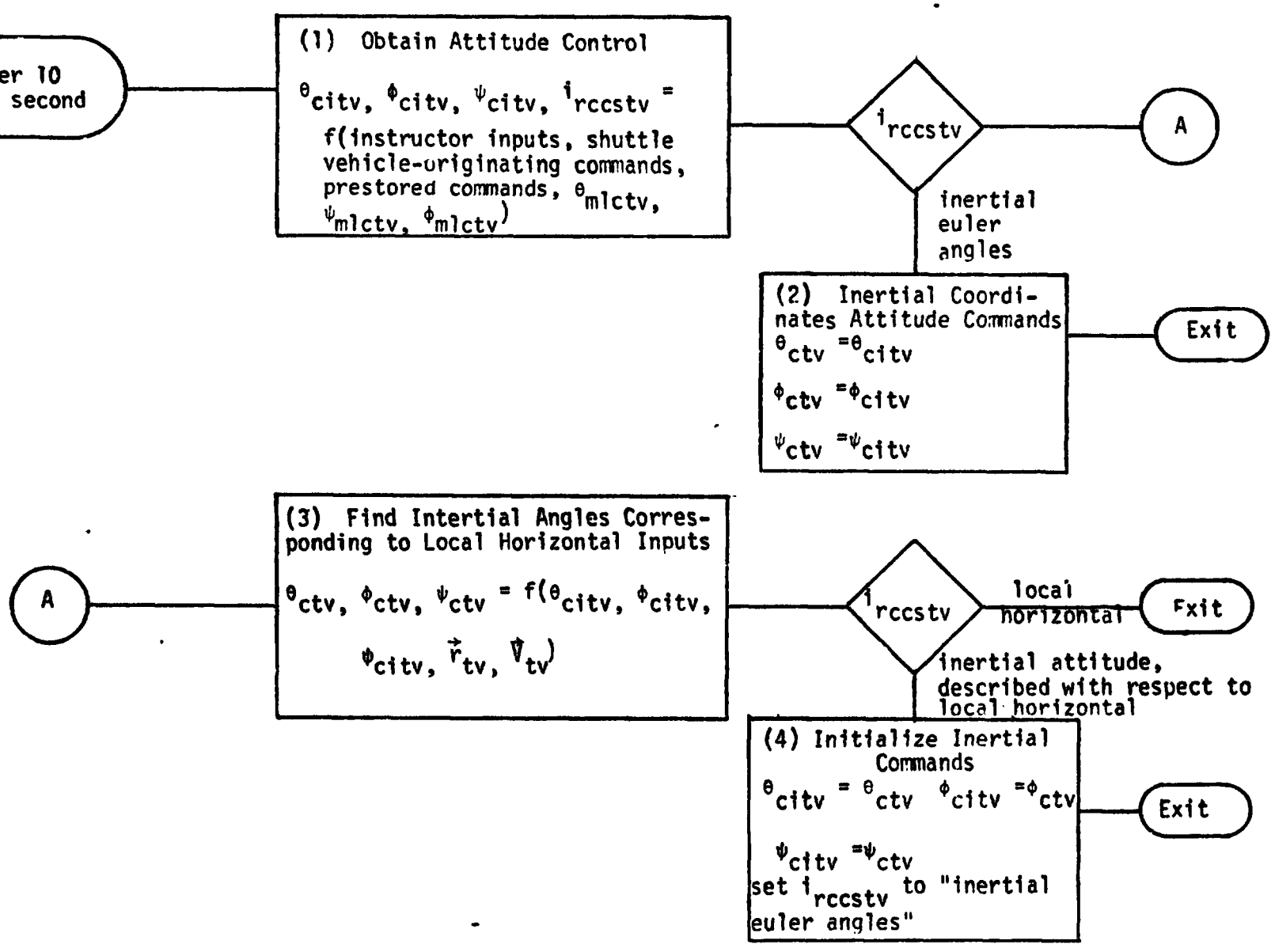
Enter 10 per second
(1) Obtain Attitude Control
θ_{citv}, ϕ_{citv}, ψ_{citv}, i_{rccstv} = f(instructor inputs, shuttle vehicle-originating commands, prestored commands, θ_{mlctv}, ψ_{mlctv}, ϕ_{mlctv})
i_{rccstv}
A
inertial euler angles
(2) Inertial Coordinates Attitude Commands
$\theta_{ctv} = \theta_{citv}$
$\phi_{ctv} = \phi_{citv}$
$\psi_{ctv} = \psi_{citv}$
Exit
A
(3) Find Intertial Angles Corresponding to Local Horizontal Inputs
θ_{ctv}, ϕ_{ctv}, ψ_{ctv} = f(θ_{citv}, ϕ_{citv}, ψ_{citv}, $\vec{r}_{tv}$, $\vec{V}_{tv}$)
i_{rccstv}
local horizontal
Exit
inertial attitude, described with respect to local horizontal
(4) Initialize Inertial Commands
$\theta_{citv} = \theta_{ctv}$ $\phi_{citv} = \phi_{ctv}$
$\psi_{citv} = \psi_{ctv}$
set i_{rccstv} to "inertial euler angles"
Exit

FIGURE 4.3.6.11.-1

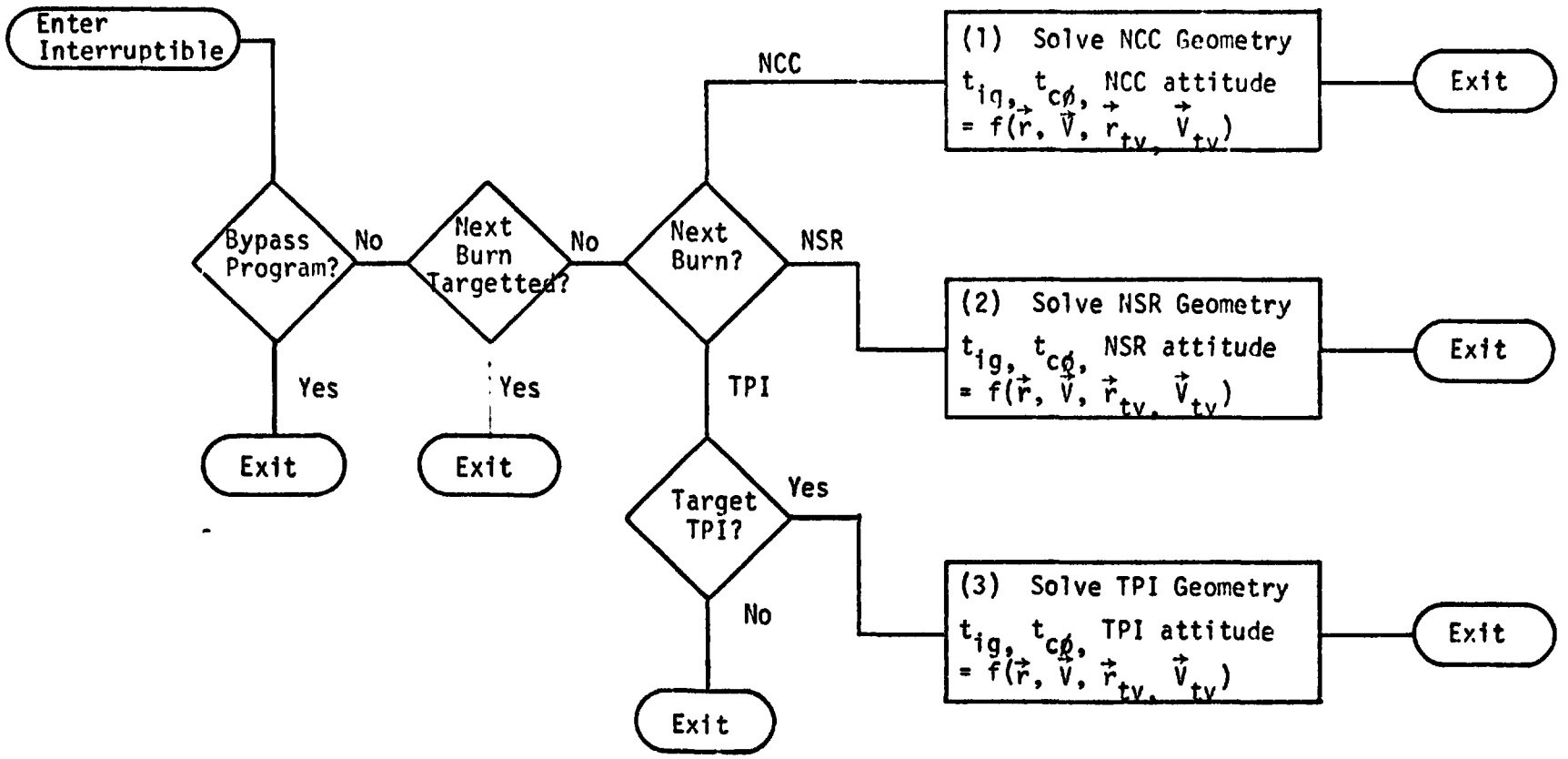

FIGURE 4.3.6.11.-2

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Symbol Dictionary for Figures 4.3.6.11-1 and 4.3.6.11.-2

i_{rccstv}	coordinate system indicator for attitude command
$\vec{r}$	shuttle position
$\vec{r}_{tv}$	target vehicle position
$t_{c\phi}$	burn cutoff time
t_{ig}	burn ignition time
$\vec{V}$	shuttle velocity
$\vec{V}_{TV}$	target vehicle velocity
θ_{ctv}	inertial pitch command to jet logic
θ_{citv}	input pitch command
ϕ_{ctv}	inertial roll command to jet logic
ϕ_{citv}	input roll command
ψ_{ctv}	inertial yaw command to jet logic
ψ_{citv}	input yaw command

4.3.7 Simulator Environment

4.3.7.1 Aural Cue

The aural simulation will consist of those audible cues which provide the crew member with vehicle operational performance characteristics during flight. Electromechanical devices are provided with appropriate software driven cues which control the audio volume, frequency, and spectrum bandwidth. Exact volume levels, frequency and spectrum bandwidth are required for each simulated device. These levels will be taken from either experimental data or calculation estimates.

The main liquid fuel rocket engine simulation will have sounds associated with burning, to include rough burn. The noise level of an engine will decrease when throttled. The engines have both fuel and oxidizer pumps which will be heard during fuel dump. There are three main engines to be simulated, each of which may be firing at a separate time. Provision will be included for simulation of multiple engines. Prior to start and post firing, metal expansion and contraction noises will be provided. Prior to reentry the main rocket engines purging will be simulated by a muted gas expansion type noise.

The two large solid rocket motors will be simulated for appropriate thrust sound and acoustic vibration. Start-up and shut-down transient noises will not be provided during normal main SRM burning. Malfunction transients will be simulated for case burnthrough. Upon thrust termination of these motors, the sound will be decreased dependent on separation distance and air density. Mechanical noises associated

with separation should not be heard over the separation rocket noise; however, this cue will be simulated for malfunction training when the separation rockets do not fire.

The airbreathing engines' audible cues generated will include booster pump whines and explosion heard during engine start. Following start-up, a turbine whine will simulate build up to run level and continue until shut-down. During airstart, this whine will also be generated. At this time, it is assumed that the jet engines will have thrust reversal capability and the accompanying noise cue will be generated.

The external fuel-oxidizer tank simulation will create noises associated with pyrotechnic line separators, fuel and oxidizer venting prior to separation, and separation system pneumatic and mechanical thumps.

Reaction control thruster and OMS jets firing cues will be provided. The RCS thrusters are located in the orbiter nose section and each of the aft OMS pods. The aural cue system will cause a sound on activation identifiable as to direction.

Docking sounds will be simulated for the mechanics of door opening, docking ring extension, mating, locking and the pneumatic shock absorber system. More definition is required to determine the metallic sounds to be simulated and the shock absorber pneumatic sounds.

The sounds associated with the payload area and payload deployment involve the latching and unlatching of payload doors, payload and radiator units. Hydraulic sounds will be provided for radiator

deployment, door mechanics, and the payload manipulator. Various levels of mechanical matings will be simulated for door openings and closing, radiator deployment and retraction, manipulator mating and stowage, and payload mating with external vehicles, or return of payloads to the payload bay. Emergency jettisoning of the manipulator will be simulated by noises associated with pyrotechnic separator devices.

The simulation of the electrical system operating off the APU's and inverters will produce a 400 hertz hum. The APU will have an explosive start-up sound with a 12,000 hertz run mode background noise. There are three APU's which may be started independently.

Fuel cell venting will be simulated by pressure build up to trip limit. This sound will probably be a pop (valve opening) followed by an air hiss.

Environmental air-conditioning sounds heard when the cabin is pressurized will be valves popping - high pressure air release - and air pressurization or evacuation during EVA/IVA activity. The volume of sound will be simulated dependent upon calculated air density.

The aerodynamic control surfaces will generate a hydraulic cue when driving from one position to another. In atmosphere, an air flow noise will be generated which is a function of dynamic pressure and the amount of total surface deflection.

The aerodynamic forces will create aural cues of wind noise, turbulence, and buffeting. During reentry phases metal expansion and contraction will cause various popping and cracking sounds.

The drag chute system will cause two minor sounds; a thump on opening of the drag chute container system and a second thump on opening of the main chute.

The landing gear system simulation will have sounds associated with the gear doors opening and closing (hydraulic cylinder activation). When the gear door begins opening, an air noise will be generated. The volume would be dependent upon air density and poor position. A mechanical thump will be generated with the gear door opening or closing. The gear deployment and retraction will create sounds associated with hydraulic motor activation. When the gear is fully extended or retracted, a mechanical thump will be generated. Noises will be generated upon operation of the breaks. Noises will also be generated from tire vibration, nose wheel shimmy, and tire contact with the runway on landing.

The audio cues of the Caution and Warning System will be simulated and triggered by software generated cues for such items as Caution, Warning, Emergency Pressure Loss, Emergency Fire, Landing Gear Not Down, and Crew Alert. These audio cues are assumed to be similar to the presently used cues for the skylab mission.

The following figure is used to graphically depict the assorted functions of Aural Cue:

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AUPAL CUE

Figure 4.3.7.1-1

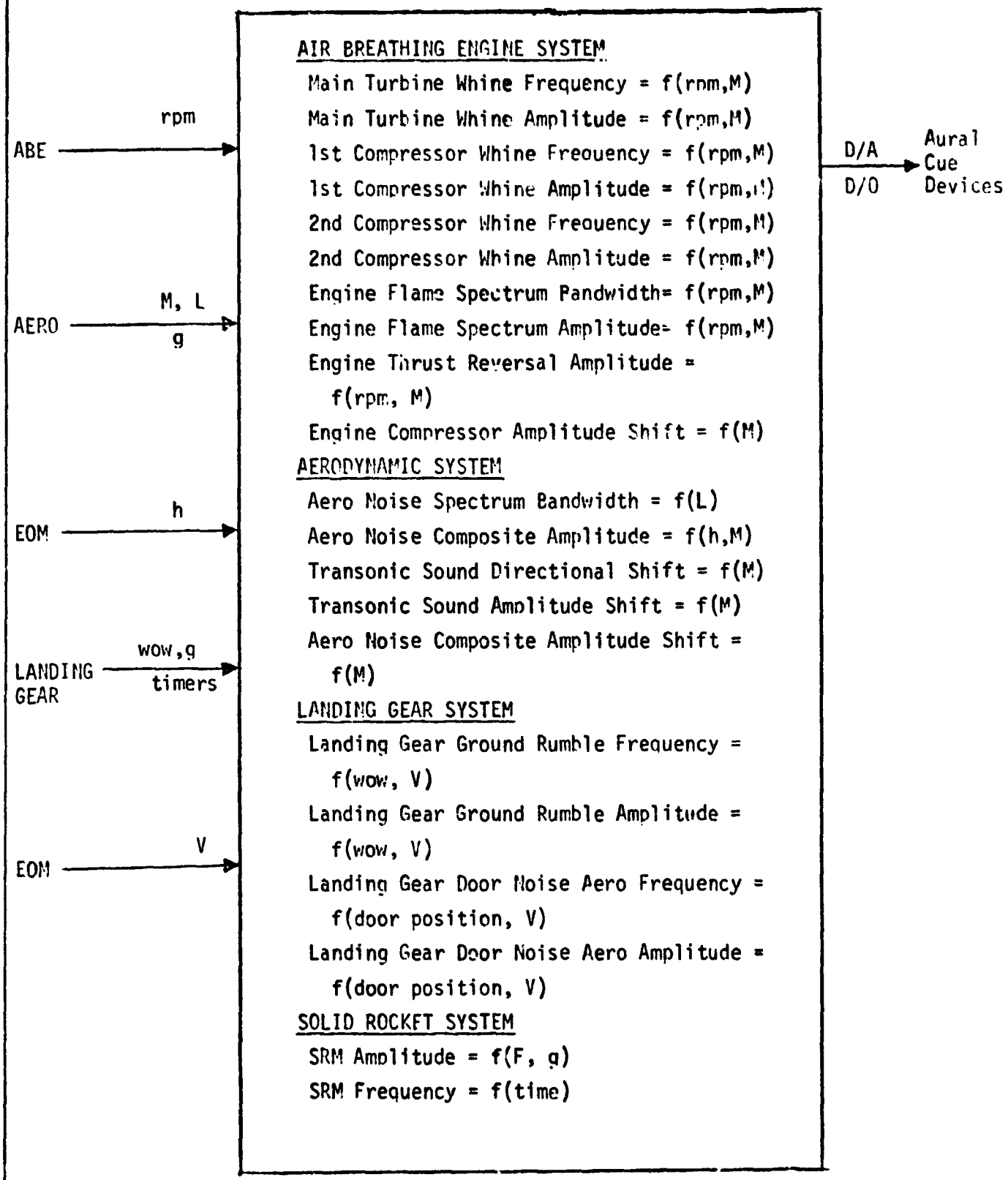
ABE
rpm
AERO
M, L
g
EOM
h
LANDING GEAR
wow, g
timers
EOM
V
AIR BREATHING ENGINE SYSTEM
Main Turbine Whine Frequency = f(rpm,M)
Main Turbine Whine Amplitude = f(rpm,M)
1st Compressor Whine Frequency = f(rpm,M)
1st Compressor Whine Amplitude = f(rpm,M)
2nd Compressor Whine Frequency = f(rpm,M)
2nd Compressor Whine Amplitude = f(rpm,M)
Engine Flame Spectrum Bandwidth= f(rpm,M)
Engine Flame Spectrum Amplitude= f(rpm,M)
Engine Thrust Reversal Amplitude = f(rpm, M)
Engine Compressor Amplitude Shift = f(M)
AERODYNAMIC SYSTEM
Aero Noise Spectrum Bandwidth = f(L)
Aero Noise Composite Amplitude = f(h,M)
Transonic Sound Directional Shift = f(M)
Transonic Sound Amplitude Shift = f(M)
Aero Noise Composite Amplitude Shift = f(M)
LANDING GEAR SYSTEM
Landing Gear Ground Rumble Frequency = f(wow, V)
Landing Gear Ground Rumble Amplitude = f(wow, V)
Landing Gear Door Noise Aero Frequency = f(door position, V)
Landing Gear Door Noise Aero Amplitude = f(door position, V)
SOLID ROCKET SYSTEM
SRM Amplitude = f(F, g)
SRM Frequency = f(time)
D/A
D/O
Aural Cue Devices

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Figure 4.3.7.1-1(continued)

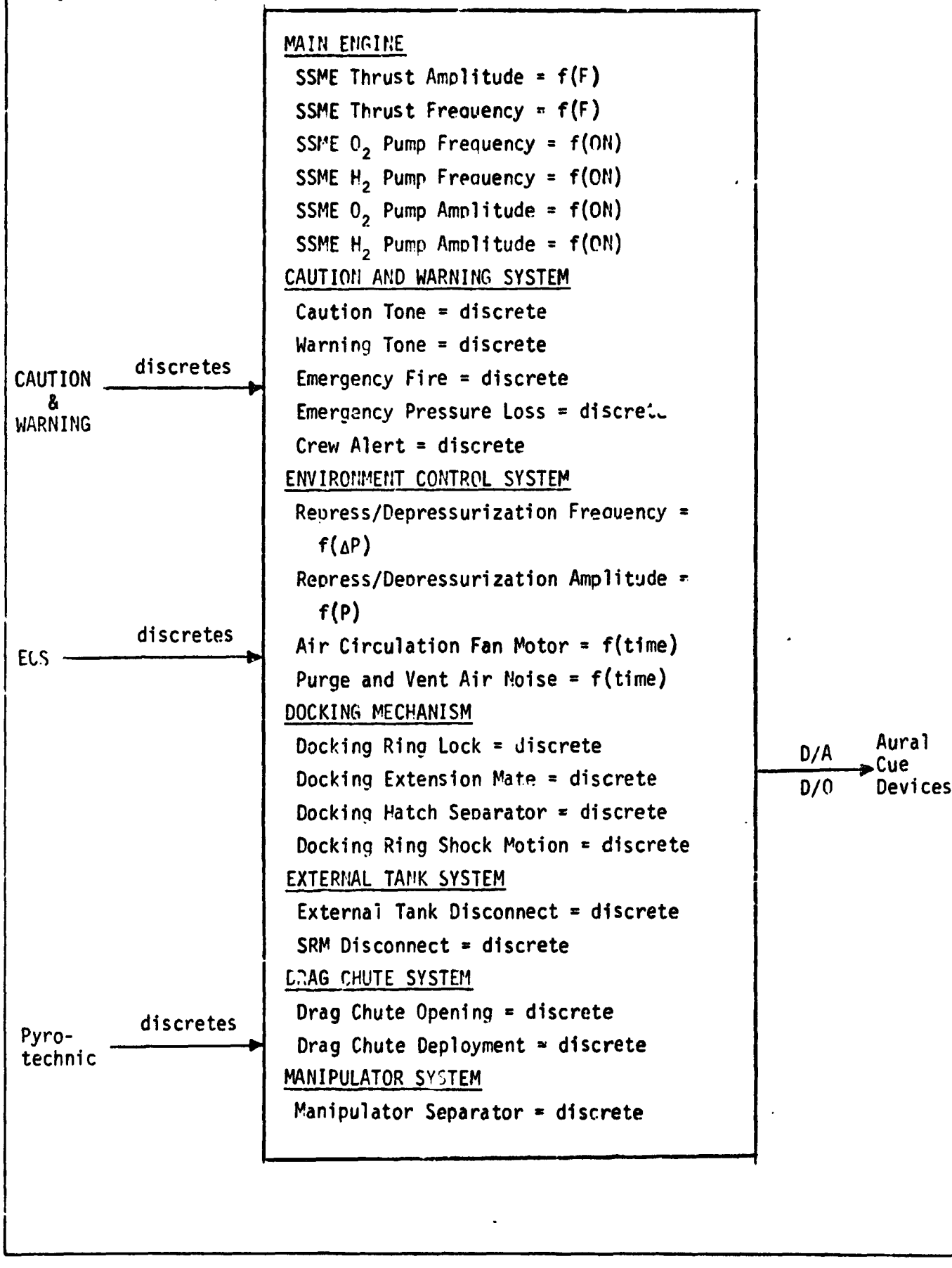
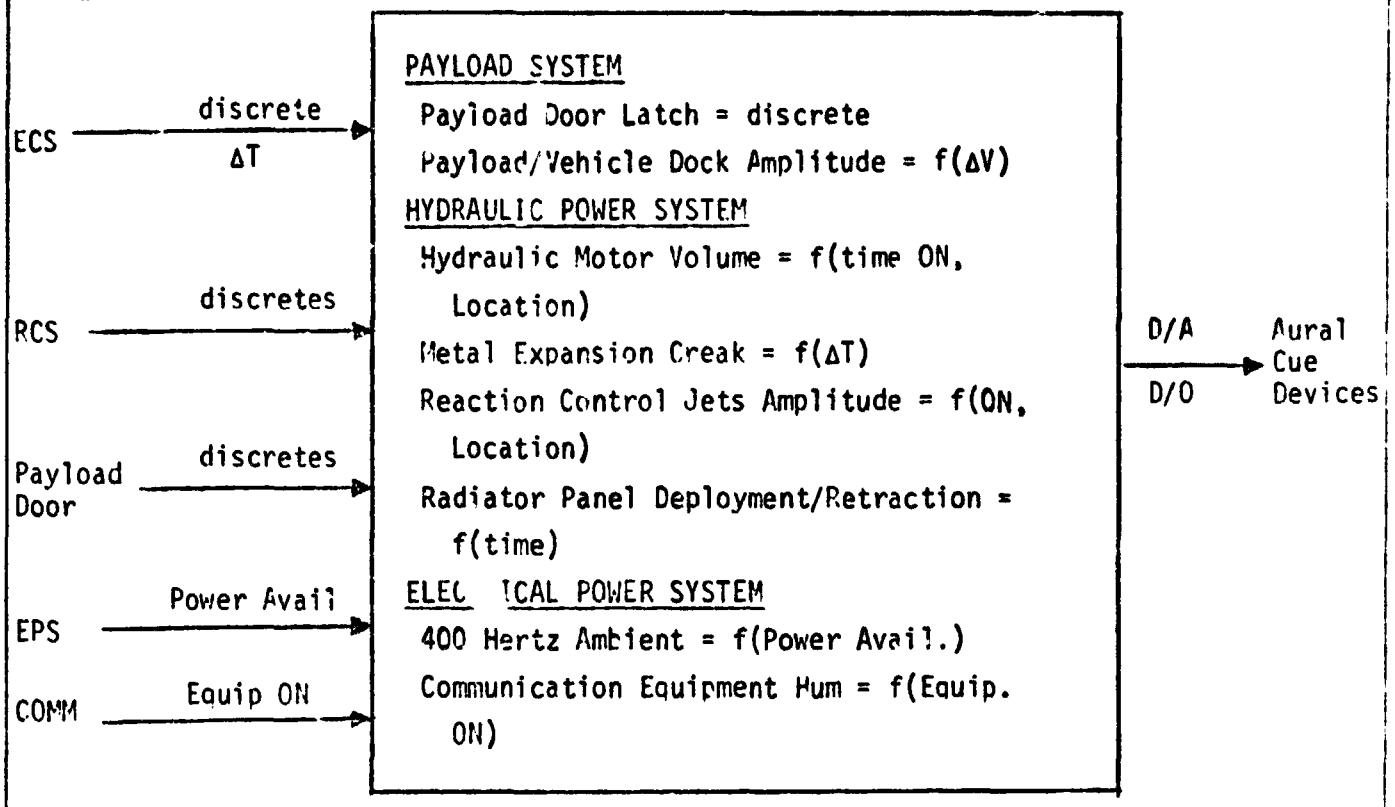


Figure 4.3.7.1-1 (continued)



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4.3.7.2 Visual (Aft)

The aft visual simulation software for the fixed base crew station will accept inputs from the simulated Equations of Motion and Payload Accommodation Systems and generate driving commands for the aft visual system. The control software configuration is highly dependent upon the final aft visual hardware design selected. Assumptions were made in order to accomplish the computer requirements as follows:

RENDEZVOUS TARGETS: Assumed Computer Image Generation (CIG) of two targets maximum simultaneous. Signal requirements are: own vehicle position and attitude, target vehicle position and attitude, target description.

STAR FIELD: Assumed CIG with signal requirements of: own vehicle position and attitude ephemeris and window angles.

VEHICLE FIXED GEOMETRY: Assumed the only signal requirements are discretes.

VEHICLE DYNAMIC GEOMETRY: Assumed three payload bay compartments (6 Doors). Signal requirements are each door position.

MANIPULATORS: Assumed CIG signal requirements for 7 DOF for each Arm.

4.3.7.3 Visual (Forward)

The forward visual simulation software will accept inputs from the simulated Equations of Motion, and generate driving commands for the forward visual system. The control software configuration is highly dependent upon the final forward visual hardware design selected. Assumptions were made in order to accomplish the computer requirements as follows:

VEHICLE GEOMETRY: Assumed signal requirements are discretes for SRM-1, SRM-2, External Tank, Each SRM Thrust Termination.

EARTH SCENE: Assumed dual orbital scene generators of an earth scnene for use at high altitudes. Signal requirements are vehicle state vector functions.

VISUAL MODEL A: Based on an instruction count from the L&A model drive, plus 25% spare.

VISUAL MODEL B: Assumed a high altitude landing scene requiring 1/2 accuracy of Model A. Based on L&A model drive, plus 25% spare. Models A & B are mutually exclusive.

RENDEZVOUS TARGETS: Assumed same requirements as for AFT windows.

STAR FIELD: Assumed same requirements as for AFT windows.

CLOUDS AND FOG: Assumed signal requirements are for discretes only.

4.3.7.4 Motion System

The software package described assumes a hardware configuration of a six degree-of-freedom motion system with the addition of a simulator crew station tilt capable of 0 to +77 degrees angle and a rate of (TBD) degrees/second. Additional crew station deflection beyond 77° can be obtained from the standard 6 DOF system. The drive philosopny considered is to program the motion system to,as realistically as possible, approximate the forces acting on the crew during actual flight. The standard 6 DOF system is capable of providing all motion cues except for long-term sustained accelerations. These accelerations occur primarily along the vehicle X axis (A_x). The hardware/software system accomplishes the long-term accelerations by directing the actual gravity force to correspond to the total sustained acceleration acting on the crew for the simulated condition. Since, in orbital flight, the gravity force is effectively cancelled by centrifugal force, a "natural" upright seating position is assumed for zero force, while a deflection of 90° is assumed for maximum force during accelerated flight. A design goal for the shuttle program is to limit the total acceleration to 3 G. Therefore, the simulator is scaled to adequately cover this range, plus an off-nominal additional acceleration. A total of 3.1 G is chosen for 90° deflection of the system for long-term accelerations. An additional requirement for all axes of the motion system is felt to be an ability to adjust scaling easily. This is because the chosen scaling will probably require adjustment based on user experience with the simulator.

Scaling and rate characteristics of the design motion system should be able to handle all longitudinal accelerations and rates of acceleration change during a shuttle mission except the rate of acceleration change at main engine

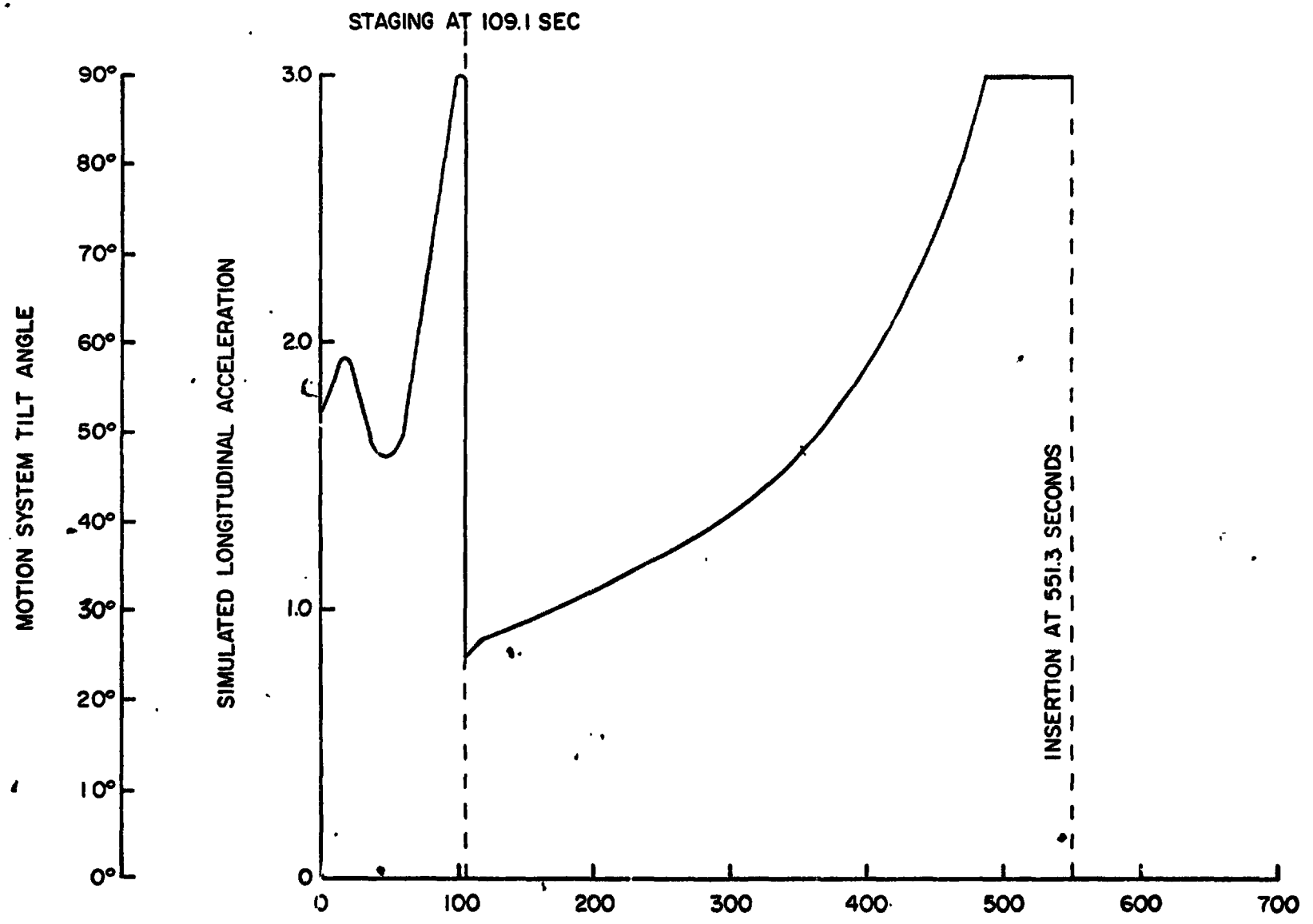

FIGURE 4.3.7.4-1

TILT vs. ACCELERATION

A = Real World SSME Emergency Thrust Termination Profile (G's).

B = Composite Simulator Tilt Angle Profile after SSME emergency thrust termination (degrees).

C = Normal SRB Thrust Termination Profile (G's).

C = Composite Tilt Angle during SRB thrust termination (degrees).

NOTE: The upper portion of B includes parallel derotation of the pitch and tilt axes. The lower portion is due to tilt axis derotation only.

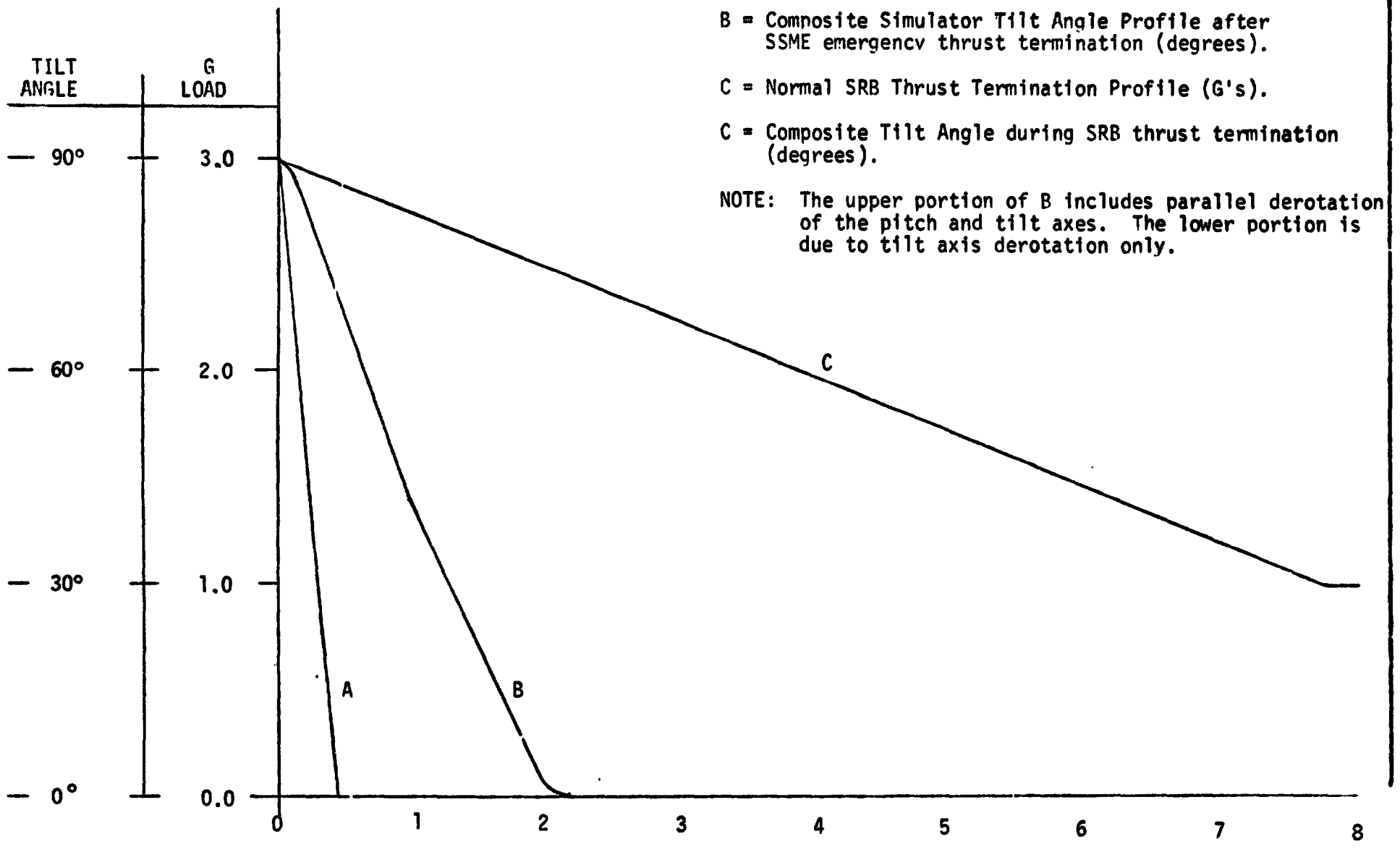

FIGURE 4.3.7.4-2

cutoff upon orbit insertion, and upon thrust termination for certain aborts. The accompanying figure illustrates nominal boost accelerations. At main engine cutoff, maximum acceleration decay is about 7.5 g/second, porportional to about 200 degrees/second at motion base scaling. A 200 degree/second rate will obviously cause hardware problems in implementation. Such a rate would also briefly result in false motion cues. The actual cue is a rather sudden cessation of great force driving the astronaut back into his couch. The 200 degrees/second motion base motion will introduce false rotational cues. However, all these cues exist for such a short period of time that they should not be too alarming. Moreover, relatively subtle differences are difficult to note when engaged in a very sizable motion cue such as cutoff. A substantially slower rate would ease hardware difficulties, and false rotational cues. It would, however, make simulated tailoff motion cues last much longer than the real-world motion cues do. Thus, it, too, would create a false cue. The short duration false cue is considered preferable to a long duration false cue. Thus, it is desirable to drive out the tilt at the largest possible maximum rate at main engine cutoff, or aborts which exhibit similar real-world cues.

The standard Singer 6 DOF motion system software is capable of accurate simulation of all motion cues except those requiring use of the added tilt feature. The added tilt feature can be driven properly with the addition of the following two equations to the standard Singer software:

$$\theta_1 = \theta_1 + K_1\left(\frac{A_x}{3.1} - \theta_1\right)\Big|_0^{77°}$$

$$\theta_2 = \text{maximum of } \{0., (\theta_1 + K_2 \frac{A_x}{3.1} - \frac{77}{90})\}$$

where

A_x = total longitudinal acceleration

K_1 = rate limiting constant

K_2 = scaling constant

θ_1 = tilt axis angle

θ_2 = tilt term of 6 DOF pitch axis

With reference to figure 4.3.7.4.1, the range of tilt required for the nominal mission is 0° to 90° representing 0 to 3G longitudinal acceleration. Since the tilt axis is baselined to a capability of 0 to 77° rotation, the 13° tilt required for the range is accomplished by the pitch axis of the 6 DOF system. In implementation, software savings can be realized by making this range the first 13°. Negative acceleration (tilt down) during entry mode will then use the same term. Off-nominal burns of SRB's or malfunctioned throttling of the Main Engine could cause greater than 3G longitudinal acceleration. This over-acceleration will be represented by use of the 6 DOF pitch axis to cover the range of tilt up to a maximum of 109° which is equivalent to 3.63G.

In order to follow the acceleration profile, three critical areas must be considered in the Boost profile.

First, the liftoff is essentially a step-function. Since the vehicle is initially on the pad in a pitched-up attitude (weight of the crew on the back), the motion system tilt will be initialized in this attitude (to 50°) as a constant until liftoff. Rapid response of the motion system is therefore avoided.

The second critical point is at SRB burnout. The SRB cores are expected to be tapered to provide a gradual decay of thrust force. Using the SHUCS data generated by the Boeing Company dated February 5, 1973, this acceleration decay is approximately 1/3 G/second. As can be seen in figure 4.3.7.4-1, the acceleration from the Main Engines alone at this point is approximately .75G. Since the tilt axis covers the range .433G to 3.0G, the acceleration profile is accomplished by derotation of the tilt axis at an average rate of approximately 10°/second. This is well within the capability of the baselined system.

The third critical point also occurs in the boost mode. See figure 4.3.7.4-2. This is either at orbit insertion or an abort from 3G longitudinal acceleration. In either case, the maximum rate of the tilt system is exceeded. Singer experinece on the T-27 Space Flight Simulator, which used the same philosophy for tilt, has shown that the lag in the longitudinal acceleration cue at orbit insertion is not a problem. The change in crew duties at orbit insertion generally do not require a fast response. The lag at launch abort, particularly if accomplished under very significant dynamic pressure, appears critical. The main engines thrust decays at a rate of approximately 7.5G/second in emergency shut-down. To duplicate this curve would require a derotation of the tilt at 225°/second average rate. The baselined system is expected to be capable of 40°/second for the tilt axis and 15°/second for the platform derotated in parallel (average rates). The tilt will therefore be derotated to 42.6° after .86 seconds and to zero after 1.925 seconds (plus wash-out times) compared to the real world requirement of .19 and .4 seconds.

Some improvement in performance of the derotation could be realized by increasing the proportion of tilt provided by the platform. However, the combined rate is 55°/second resulting in 1.64 seconds for 100% wash-out. The improvement is probably not worth the software cost of implementing - especially since the added pitch platform excursion reduces the pitching capability.

4.3.7.5. MCC Interface TLM, DCS, Trajectory

The computer-to-computer interfaces between the Mission Control Center and the Shuttle Mission Simulator will be accomplished by providing interface buffers and hard line data transfer equipment between the two computers. The seven general buffer areas required in the SMS computer complex is shown pictorially in Figure 4.3.7.5.

The Target Vehicle buffer will consist of approximately six words of data containing target vehicle indentification, three commanded attitude words, a horizontal or vertical reference word, a time ignition word, and the time of burn. This data will enable MCC to maneuver the simulated target vehicles in the SMS by command and for the simulation of the target vehicle dynamics to be realistic for visual conditions.

The Digital Command System or the Up Data Link will be simulated by the SMS computer buffer accepting and decoding the MCC created command words. These commands provide the communication link for transfer of the MCC computed state vector data to the Shuttle GNC computer. The transferred state vector should contain ground equipment and data reduction propagated errors similar to the real world. System commands will be decoded by the DCS program for use by the vehicle systems.

The computer mode of operation and time will be transferred on a two-way basis with both computers providing data to the other. Master clock time data words will be generated by MCC for use in the SMS. In non-integrated modes the SMS will provide it's own time base.

The trajectory data buffer provides the master event time data and state vector data. The data buffer will provide for unpacking two words of discrete configuration data parameters, and time words for frame time and liftoff time.

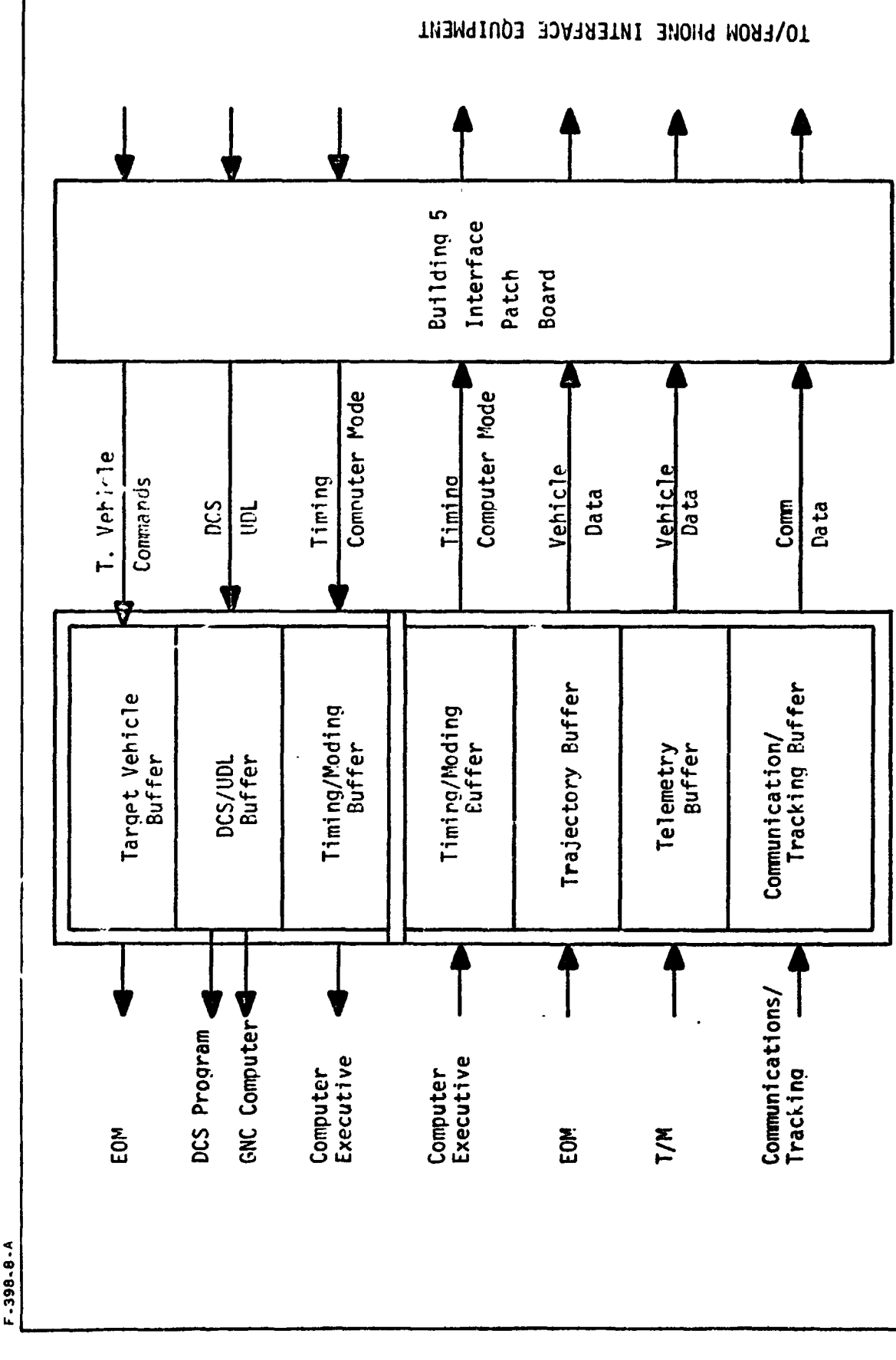

Figure 4.3.7.5-1
SMS INTERFACE-COMPUTER BUFFER

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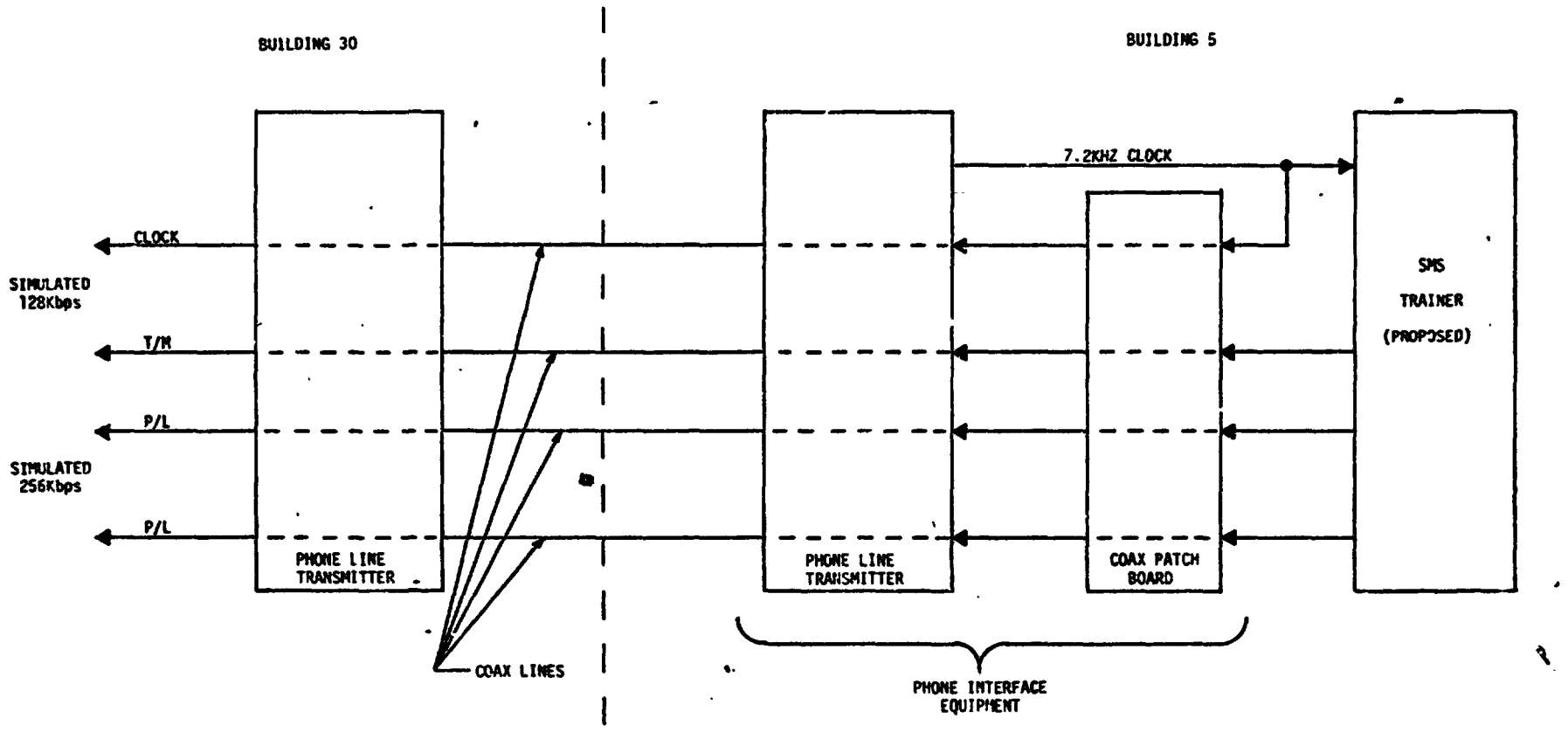
Vehicle data for state vector position and attitude are supplied to GSSC/MCC for nine target vehicles and the shuttle. The nine target vehicles include the two solid rocket engines, the external tank, a free flying vehicle, and five payload targets. The packed discretes will identify whether the targets are attached or unattached.

The shuttle vehicle telemetry data will be provided to MCC by blocks over coax cable. The data block transfer rate will be established at ten per second or 52Kbs. Spare coax cable will allow simultaneous transmission of the payload 1.7 MHZ data when that task trainer(s) is added. No software is provided for payload dedicated telemetry on the 1.7 MHZ subcarrier. Payload data which is transmitted on the 1.024 MHZ subcarrier will be provided. The maximum rate of data transfer over existing equipment is approximately one-half the real world system rate of 128 Kbs.

The communication/tracking buffer will provide voice and data recorder status and transceiver status along with transmitter output power to MCC. MCC will be required to calculate if an air to ground voice/data link is possible.

Each of these buffer areas may be combined with other buffer areas so as to fully use the data transmission link capability. Typical overall interfaces between the computers in Building 5 and the GSSC/MCC complex is shown in the following figures.



4.3.7.6.-2 TELEMETRY INTERFACE

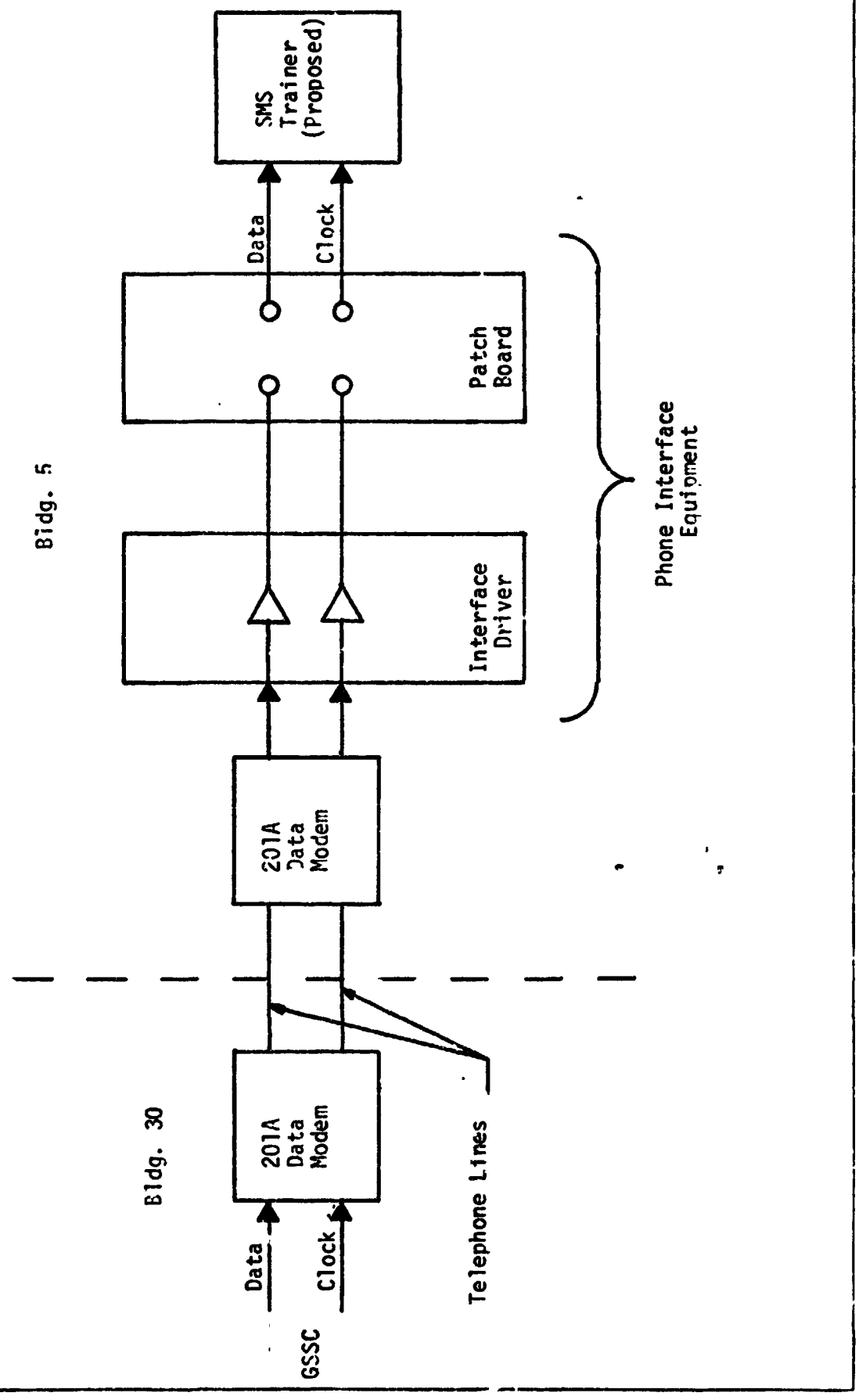


Figure 4.3.7.5.-3 Command Interface Bldg. 30/Bldg. 5

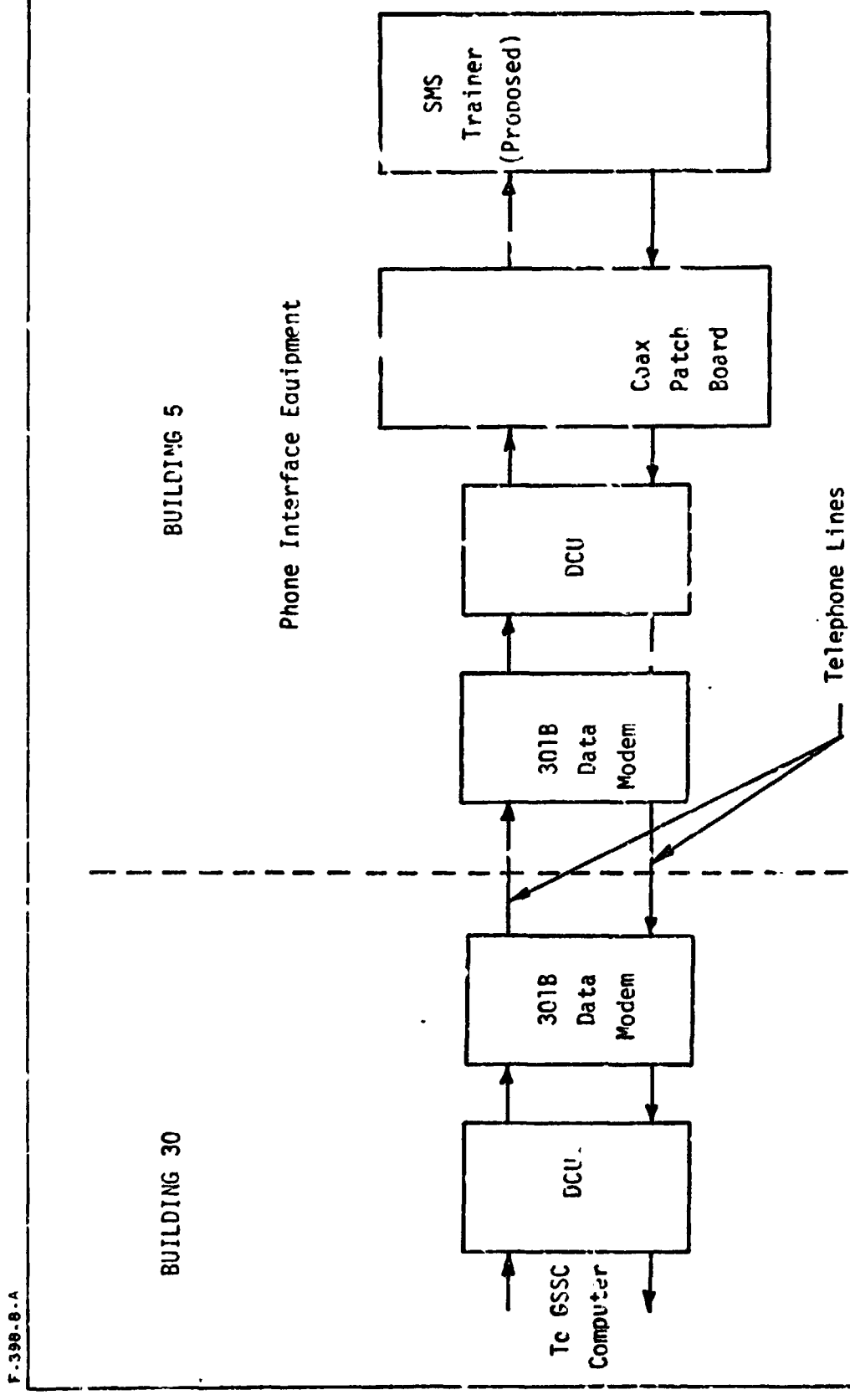


Figure 4.3.7.5.-4 SMS TRAJECTORY, TIMING, MODE, COMMUNICATION, AND TARGET VEHICLE INTERFACE

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4.3.7.6 Instructor Aids

The shuttle systems instructor will be provided with computer generated displays to reduce simulator data into a more directly useable training tool. These displays will use both digital and graphics as a means of presentation of data. The displays will also provide software system test and checkout capability without using crew station meters and displays. In addition parameters generated for internal software simulation usage will be provided.

The following examples are used to indicate the types of displays that are feasible and in some cases are in use in existing simulators.

A combination of graphics and digital display will be used for the electrical system power balance and distribution. The display will contain nodal current summations, bus voltages, inter-bus currents, and inter-bus circuit breaker status. Another display will be dedicated to a summation of the individual and collective bus loads for the AC buses and DC buses. Individual displays will also be provided for relay state, voltage, current, heat, malfunctions active for various components of the electrical system such as regulators, batteries, chargers, inverters, and generators. This type of presentation is typical of all systems for the on-board system test and support displays.

"Predicter" displays will provide the instructor a means of determining the condition or state of consumables, energy, or communication linkage at a future time point. For example, the "Communication Predicter" would display the next ground station to be acquired and the estimated time until line-of-sight is acquired. This predicter is anticipated to be limited to orbital operations using STDN stations only. The Energy Management graphic display is a type of predicter which shows the estimated down range and cross-range capability of the vehicle based on its altitude, speed, and aerodynamic characteristics. The energy management display will also graphically display the primary and secondary landing sites and runway

orientation, wind direction, ideal approach pattern, etc. In addition to these displays, an estimated system capability could be displayed for electrical consumption rate versus total power available (from batteries, APU's, fuel cells, etc.) or for water consumption versus water quantity on hand and fuel cell water to be generated. Such displays would provide the instructor with a means of estimating vehicle status at a future time point based on inserted system malfunctions. A ground track predictor display could be used to display recent and anticipated ground track against continental outlines and STDN stations (and their approximate communication ranges) during orbital operations. Capabilities similar to those of the current CMS ALOS program could be provided, including sequential lists of STDN stations to be acquired over an interval of future time, and their acquisition and loss times (assuming no burns) during orbital operations. A capability could be provided to calculate time of closest ground track approach on the next orbit to a given earth location, as well as other parameters at the instant of closest approach such as altitude, range and bearing to the ground location, and line-of-sight elevation angle at the ground location.

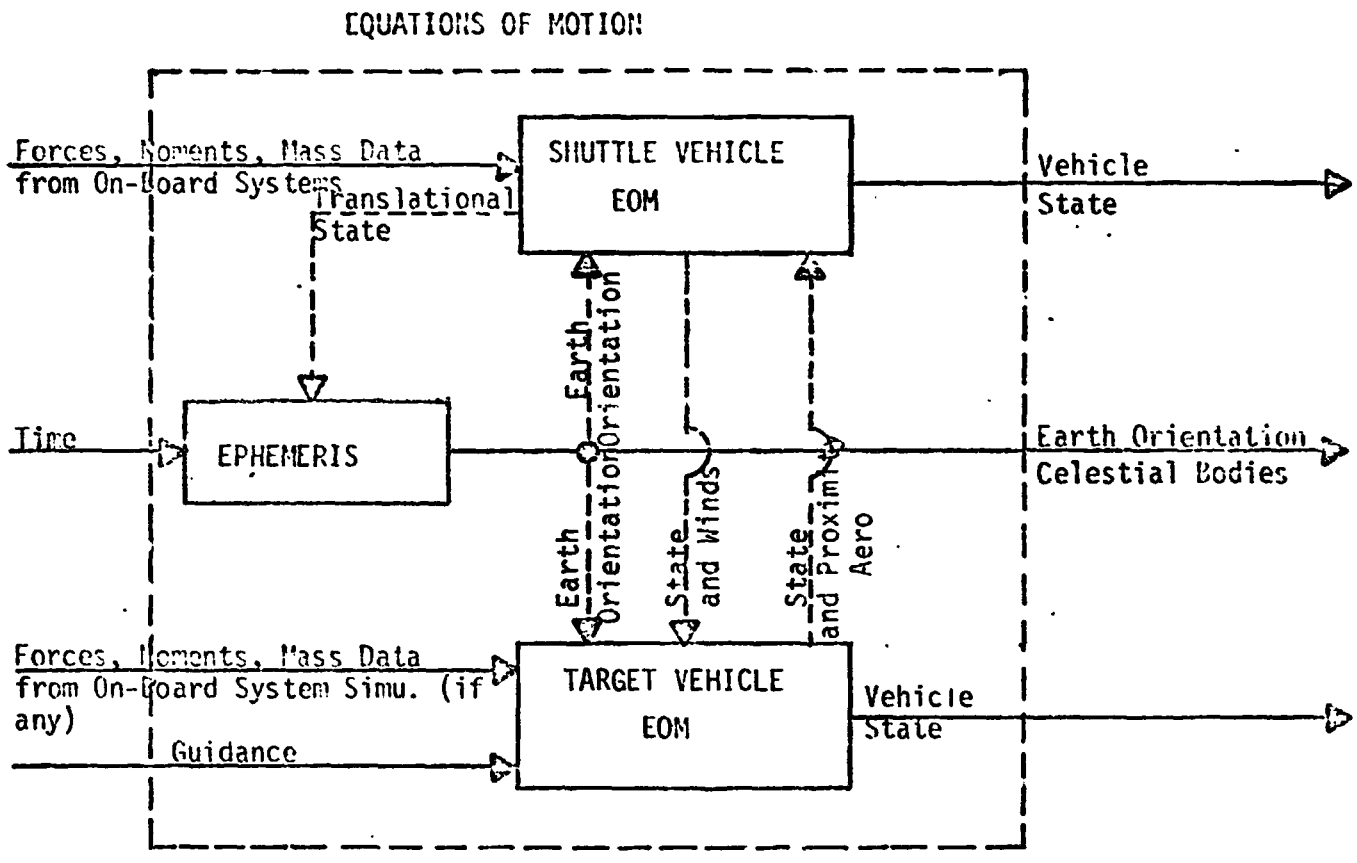
A state vector generation program similar to the CMS STAT program could be included, to permit trajectory reset of the shuttle or a target vehicle to any desired translational state. That translational state could be specified by ordinary rectangular coordinates in any of several coordinate systems, by orbital elements, by ground-projected location and local horizontal velocity properties, or by any of several other methods. Assuming a MCC role in orbital burn targetting, a package of targetting and burn sequencing programs could be provided for instructor use operating directly off simulator EOM data. Such a system, similar to that currently existing in the CMS MTP program package, would permit the instructor to "simulate" the RTCC, and possess information analogous to that of a MCC controller. Existing CMS targetting programs output such data as burn time, burn duration,

velocity to be gained along each axis, burn attitude, etc.

The use of an all attitude platform will reduce platform alignment problems, and increased shuttle autonomy may further impact ground participation in platform realignment. However, it is desirable to avoid the "gimbal-flip" region with 4-gimbal platforms, so platform realignments may still be made. If the ground has a role in this activity, an alignment generating routine analogous to the CMS RFMT program may be desirable.

4.3.8 Equations of Motion

The equations of motion system will simulate the dynamic and physical environment for the shuttle vehicle and each target vehicle. Inputs to the equations of motion include forces, moments, mass data from simulated on-board systems, and guidance-type inputs to the generalized target vehicle propulsion systems. The equations of motion system is conceptually subdivided as shown below:



A number of coordinate systems will be used to simulate vehicle dynamics. The following symbols will be used for coordinate systems:

T coordinate system (earth centered) - epoch at reset point

X-axis: intersection of true equator and true ecliptic at epoch, positive toward vernal equinox.

Z-axis: true earth north-polar spin axis at epoch.

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Y-axis: completes right-handed orthogonal triad.

S coordinate system (earth centered)

X-axis: intersection of mean equator and mean equinox at epoch 1950.0, positive toward vernal equinox.

Z-axis: mean earth north-polar spin axis at epoch 1950.0.

Y-axis: completes right-handed orthogonal triad.

E coordinate system (earth centered)

X-axis: intersection of earth equatorial plane and plane of Greenwich meridian, positive out at zero longitude.

Z-axis: Earth north-polar spin axis

Y-axis: completes right-handed orthogonal triad.

F coordinate system (earth surface fixed) - flat earth system

X-axis: positive north

Y-axis: positive east

Z-axis: positive down

b coordinate system (vehicle center of mass centered)

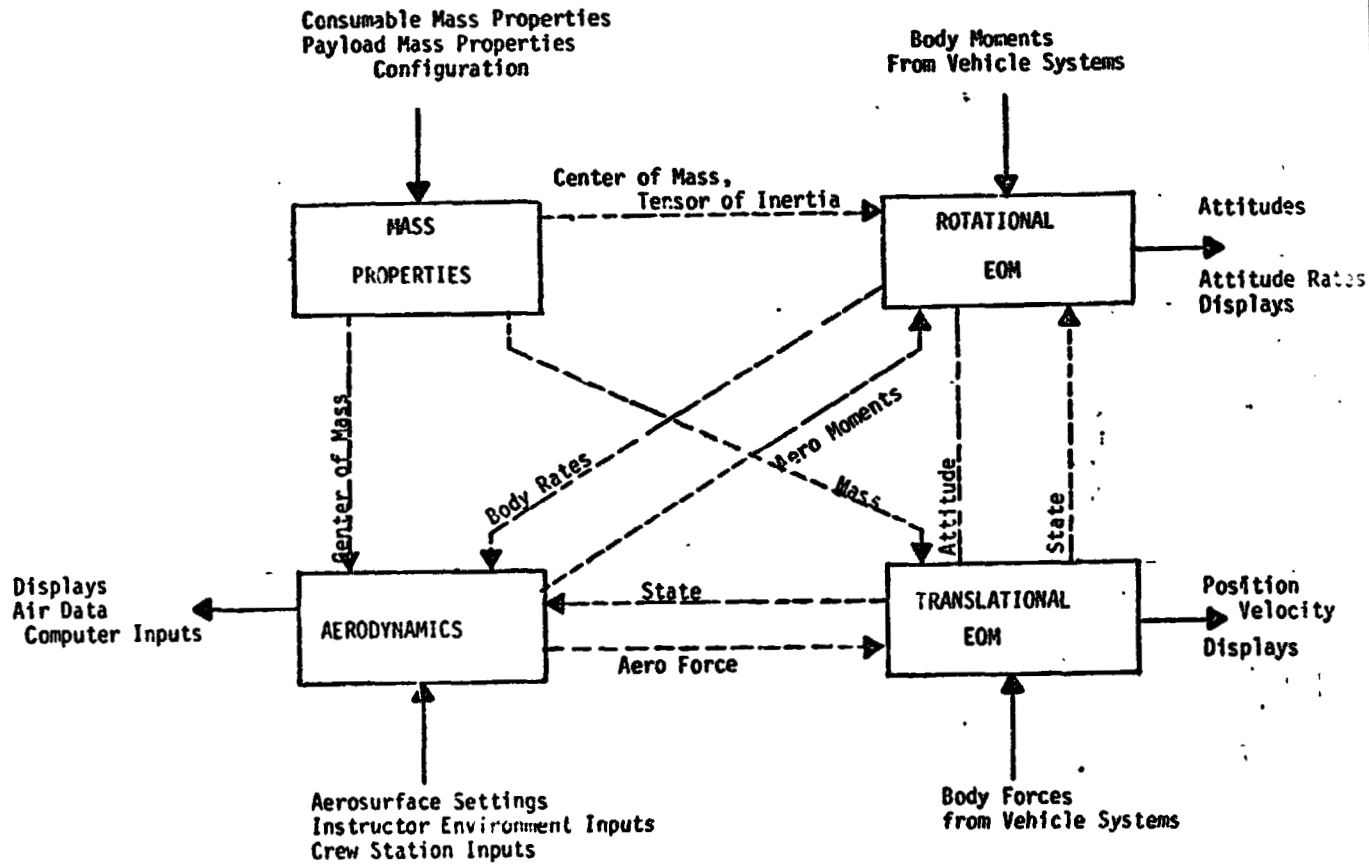
X-axis: orbiter fuselage reference line, positive forward.

Z-axis: perpendicular to X-axis in orbiter symmetry plane, positive down.

Y-axis: completes right-handed orthogonal triad.

4.3.8.1 Shuttle Vehicle

The shuttle vehicle equations of motion will provide a complete simulation of vehicle rotational and translational dynamics. The equations will operate under all shuttle vehicle space and ferry mission configurations. Inputs to the shuttle vehicle equations of motion will include body forces and moments from vehicle systems, aerosurface settings, insturctor-determined environment inputs, consumable and payload mass properties, and vehicle configuration. From this information, the position, velocity, attitude, and attitude rate will be determined, as well as other parameters listed in the following discussions. The conceptual design of the shuttle equations of motion is divided into four subsystems as illustrated below:



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4.3.8.1.1 Translational EØM

The similated shuttle vehicle translational equations of motion will maintain vehicle translational state, given body forces, vehicle mass, and vehicle orientation in terms of the direction cosine matrix relating body fixed coordinates to EØM reference coordinates. Body forces which will be summed to obtain total body force are:

SRM thrust

MPS thrust (including venting)

ØMS thrust

RCS thrust

ABPS forces

Gear/Braking forces

Drag Chute forces

Aerodynamic forces (including proximity and ground effects)

Payload Manipulation forces

Docking forces

The body forces are then transformed to the appropriate EØM reference coordinate system (T coordinate system or appropriate F coordinate system), and divided by total vehicle mass to obtain vehicle body acceleration. During orbital flight, (which may be defined as flight at orbital velocity with sustained body acceleration less than 3 $\frac{ft}{sec^2}$), an Encke orbit determination scheme together with Runge-Kutta integration will update vehicle state each 8 seconds. Vehicle state will be estimated in the intervening time by extrapolating gravity from past values calculated at 8 second intervals, and integrating directly to find velocity and position. Position and velocity deltas resulting from body accelerations will be included in the appropriate fashion into the Encke accumulated central body deviation state vector. An Encke scheme is selected over a Cowell scheme because

of the former's substantially higher accuracy, permitting a relatively larger step size with superior precision. Encke is also very preferable for accomplishing rapid step-ahead. Runge-Kutta integration is used in preference to a high-order predictor-corrector integrator (e.g., Adams-Moulton) because of Runge-Kutta's very high precision in handling such gravitational accelerations, and the fact that is is self-starting. Predictor-correctors require a number of past values which, due to the stringent accuracy requirements, would probably have to be initialized in this case using Runge-Kutta, thereby substantially complicating the program. Far less stringent accuracy requirements exist on the past values for the extrapolation, since extrapolation errors do not propagate. Update each 8 seconds should assure update "jumps" of less than 1 foot in position. During other than orbital flight, vehicle state will be maintained using a low-order predictor scheme (e.g., rectangular or Adams) and a Cowell orbit determination scheme (due to the very substantial perturbative accelerations). During pre-launch (i.e., prior to hold down arm lifting), the state vector will be re-calculated directly using the earth rotation rate, rather than integrated. State will be maintained in the T system during space flights, until final approach, at which time translation to the appropriate flat-earth F coordinate system will be accomplished. A flat-earth F coordinate system will be used for ferry flights. Gravitational accelerations will be calculated using the J_2,J_3,J_4, and J_{22} harmonics during regimes in which the T coordinate system is used. During regimes in which the F coordinate system is used, a central body gravitational field with magnitude that of 30^0 latitude will be used. Parameters output for other systems and displays at all time, will include:

vehicle state (includes vehicle altitude)

vehicle latitude and longitude

vehicle ground track heading

vehicle relate velocity

vehicle flight path angle

In regimes in which state is maintained in the T coordinate system, the following additional outputs will be provided:

vehicle altitude

vehicle radius magnitude

vehicle inertial velocity magnitude

vehicle state in S and E systems

orbital elements (semi-major axis, parameter, eccentricity, apogee, perigee, inclination, inertial logitude of ascending node, true anomaly, eccentric anomaly, inertial longitude of perigee)

time of next orbital sunrise/sunset

An iteration rate of 20 per second is specified. Since aerodynamics, MPS, RCS, and ØMS programs are iterated at this rate, a sizable part of translational RØM must operate this fast to properly interface. It is considered desirable to also operate the remainder of the program at the same rate to obtain accurate gravitational effects. Although all display parameters are shown in the conceptual design as being updated each 50 milliseconds, this is probably not necessary in all cases. Thus, if time is critical, some of these may be updated less frequently, at the cost of some complication of the conceptual design. The conceptual design is sketched in figure 4.3.20.1.1-1. All coordinate transformation, except that from B coordinates to I or F coordinates, will be calculated in block (7) or block (15) thereof. In step-ahead mode, the Encke/Runge-Kutta loop only will be used for integration (blocks (11) through (13)) and the extrapolation logic bypassed. A larger step size than 8 seconds can be utilized (one minute would not be excessive). The only non-gravitational perturbative force included during step-ahead will be orbital drag. It will be calculated using the last values of aero coefficients

and angle of attack obtained prior to entering step ahead. Dynamic pressure will be recalculated, the forces and accelerations re-computed and approximately transformed to the T coordinate system once per step-ahead step. Drag will be assumed constant over one integration step.

Enter 20 per Second

(1) Sum Body Forces
$\vec{F}_{b_b} = \Sigma$ (body forces)

(2) Transform to EOM coordinates
$\vec{F}_{b_l} = [\gamma]\ \vec{F}_{b_b}$

(3) Find body acceleration
$\vec{a}_b = \vec{F}_{b_l}/M$

Orbit? Yes → B; No → A

body forces (Aero and On-board systems)

direction cosines (Rotational EOM)

mass (Mass Properties)

body accel

Greenwich Hour Angle (Ephemeris)

A

pre-launch? No → (5) Find gravitational acceleration
$\vec{a}_g = f(\vec{r}, \theta_{GHA})$ (In T System)
$\vec{a}_g = \vec{c}$ (In L system)

(6) Integrate for velocity, position
$\vec{v} = \int(\vec{a}_b + \vec{a}_g)\,dt + \vec{V}_{old}$
$\vec{r} = \iint(\vec{a}_b + \vec{a}_g)\,dt^2 + \vec{r}_{old}$

T or L System → L System: (7) Find appropriate display parameters
$\lambda = f_1(\vec{r})$ $\gamma = f_5(\vec{V})$
$L = f_2(\vec{r})$ $\vec{r}_E = f_6(\vec{r}, \lambda, L)$
$\psi = f_3(\vec{V})$ $[\gamma]_{E/B} = f_7(\vec{r}, [\gamma])$
$V_r = f_4(\vec{V})$
→ Exit; display param.

state

T System → Trans. to L System? Yes → (14) Transform state and direction cosines from T system to L system → D

SGHA, CGHA (Ephemeris)

pre-launch? Yes → (4) Advance state
$\vec{r} = f_1(t)$
$\vec{v} = f_2(t)$
→ D; State

C

B

(8) Integrate body acceleration
$\Delta\vec{V}_b = \int\vec{a}_b\,dt + \Delta\vec{V}_b$
$\Delta\vec{r}_b = \int\int\vec{a}_b dt^2 + \Delta\vec{r}_b$

Time ≠ 4 sec. → (9) Extrapolate Gravity Effect
$\vec{a}_g = f(\tau_E$ past values)
$\Delta\vec{V}_g = \int\vec{a}_g dt + \Delta\vec{V}_g$
$\Delta\vec{r}_g = \int\int\vec{a}_g dt^2 + \Delta\vec{r}_g$

(10) Find state
$\vec{v} = \vec{v}_{upd} + \Delta\vec{V}_b + \Delta\vec{V}_g$
$\vec{r} = \vec{r}_{upd} + \Delta\vec{r}_b + \Delta\vec{r}_g + V_{upd}\,t$
→ State

= 4 sec.

t_{RKE} = 0 → (11) Find Intermediate Encke Runge-kutta terms
$\vec{a}_{g_{Rkb}} = f_1(\vec{r}_{Ref}, \vec{a}_{g_{Rka}}, \Delta\vec{r}_b)$
$\vec{a}_{g_{Rkc}} = f_2(\vec{r}_{Ref}, \vec{a}_{g_{Rka}}, \vec{a}_{g_{Rkb}}, \Delta\vec{r}_b)$
$t_{Rka} = 1$
→ C; D

t_{RKE} = 1 → (12) Find Update State
$\vec{r} = \vec{r}_{upd} = \vec{r}_{upd} + f_1(\vec{r}_{ref}, \vec{a}_{g_{Rka}}, \vec{a}_{g_{Rkb}}, \vec{a}_{g_{Rkc}}, \Delta\vec{r}_b)$
$\vec{v} = \vec{v}_{upd} = \vec{v}_{upd} + f_2(\vec{r}_{ref}, \vec{a}_{g_{Rka}}, \vec{a}_{g_{Rkb}}, \vec{a}_{g_{Rkc}}, \Delta\vec{r}_b)$
$1 = R_{ke} = 0$ $\vec{a}_{g_{Rkc}} = \vec{f}(\vec{r})$
$\Delta\vec{r}_b = \Delta\vec{V}_b = \Delta\vec{r}_g = \Delta\vec{V}_g = 0$
→ state

(13) Rectify Reference Conic If Necessary
$\vec{U}_S$ SGHA, θ_{GHA}, CGHA (Ephemeris)

(15) Find Display Parameters
$\lambda = f_1(\vec{r})$ $\vec{r}_{BSO} = f_6(\vec{r})$
$L = f_2(\vec{r}, \theta_{GHA})$ $\vec{v}_{BSO} = f_6(\vec{v})$
$h = f_3(\vec{r}, \lambda)$ $\vec{r}_E = f_7(\vec{r}, CHGA, SGHA)$
$|\vec{r}| = |\vec{r}|$ $\vec{v}_E = f_7(\vec{v}, CHGA, SGHA)$
$|\vec{v}| = |\vec{v}|$ $V_r = f_8(\vec{v}_e)$
$\gamma = f_4(\vec{r}, \vec{v})$ $\beta = f_9(v, \gamma)$
orb. elem. $= f(\vec{r}, \vec{v}, \gamma)$ $[\gamma]_{E/B} = f_{10}([\gamma], \theta_{GHA})$
$t_{sune} = f_5(\vec{U}_S, \vec{r}, \vec{v})$
→ display param.

Exit

FIGURE 4.3.8.1.1-1 TRANSLATIONAL EOM

SYMBOL DICTIONARY

$\vec{A}b$	Total body acceleration
$\vec{A}g$	Gravitational acceleration
$\vec{A}grka$	Intermediate gravitational acceleration
$\vec{A}grkb$	Intermediate gravitational acceleration
$\vec{A}grkc$	Intermediate gravitational acceleration
CGHA	Cosine of θ_{GHA}
$\vec{F}_{bb}$	total body force, B coords.
$\vec{F}_{bi}$	total body force, T or L coords.
h	vehicle altitude
$\dot{h}$	altitude rate
i_{RKL}	Runge-Kutta logic flag
L	vehicle longitude
M	total vehicle mass
$\vec{r}$	vehicle position, T or L coords.
$\vec{r}_{B50}$	Vehicle position, S coords.
$\vec{r}_E$	Encke reference vehicle position
$\vec{r}_{upd}$	vehicle position at last low speed loop update
SGHA	sine of θ_{GHA}
$\vec{V}$	vehicle velocity, T or L coords.
$\vec{V}_{B50}$	vehicle velocity, S coords.
$\vec{V}_E$	vehicle velocity, E coords
$\vec{V}upd$	vehicle velocity at last low speed update
Vr	vehicle relative velocity magnitude
γ	flight path angle
$[\gamma]$	direction cosine matrix
$[\gamma]E/B$	direction cosine matrix between E coordinates and B coordinates
$\Delta\vec{V}_b$	delta position due to body force since last update
$\Delta\vec{V}g$	delta position due to gravity since last update
$\Delta\vec{V}b$	delta velocity due to body force since last update
$\Delta\vec{V}g$	delta velocity due to gravity since last update
θ_{GHA}	Greenwich hour angle
λ	vehicle longitude
ψ	vehicle ground track heading

4.3.8.1.2 ROTATIONAL EØM

The simulated shuttle vehicle rotational equations of motion will maintain vehicle attitude and attitude rates given current vehicle position, center of mass, inertia tensor, and vehicle body forces and moments. Body force, and moments included in the calculation of vehicle rotational dynamics are:

SRM thrust

MPS thrust (including venting)

ØMS thrust

RCS thrust

ABPS forces

Gear/Braking forces

Drag chute forces

Aerodynamic moments (including proximity and ground effects)

Payload Manipulation moments

Docking Moments

Body moments resulting from body forces are calculated using the fixed position of the application point and the current position of the vehicle center of mass. The rotational effects of moving payload doors/space radiators will be calculated, and included within the rotational dynamics. Gravity gradient torques will be calculated and included in the aggregate body moments. Euler's equations will be solved to obtain angular accelerations, and will be integrated to obtain angular rates. Rates and attitude changes due to prelaunch constraints will be simulated prior to liftoff. The structural body fixed coordinate system will be used for the inertia tensor and angular velocity. The use of principal axes results in a considerably simplified form of Euler's equations. However, this advantage is largely negated if the orientation of the principal axes tend to move substantially with respect to body axes in time. Time, and especially core, required to calculate the body-to-principal axes

transformation tends to erase the advantages of principal axes, and more. It appears currently that during many mission phases, the principal axes migrate sufficiently much to require recalculation. Thus, principal axes are not used. This choice should be re-evaluated as later data becomes available. The direction cosine matrix will be obtained from the angular velocity vector using self-normalizing difference equations. Euler angles with respect to local horizontal are then calculated for purposes of display using the direction cosines. The direction cosine matrix will transform from the D coordinate system to either the T or F coordinate system, depending upon which system is the prime EOM coordinate system at the time. Rotaional dynamics should be updated 20 times per second during regimes when a thrust vector control sytem or aerosurfaces are in use for good response characteristics. At least part of the system must be iterated at that rate during orbital coast modes to properly interface with the simulated RCS. Under those circumstances, it seems desirable to iterate the program at that rate at all times. The conceptual design is illustrated in Figure 4.3.8.1.2-1.

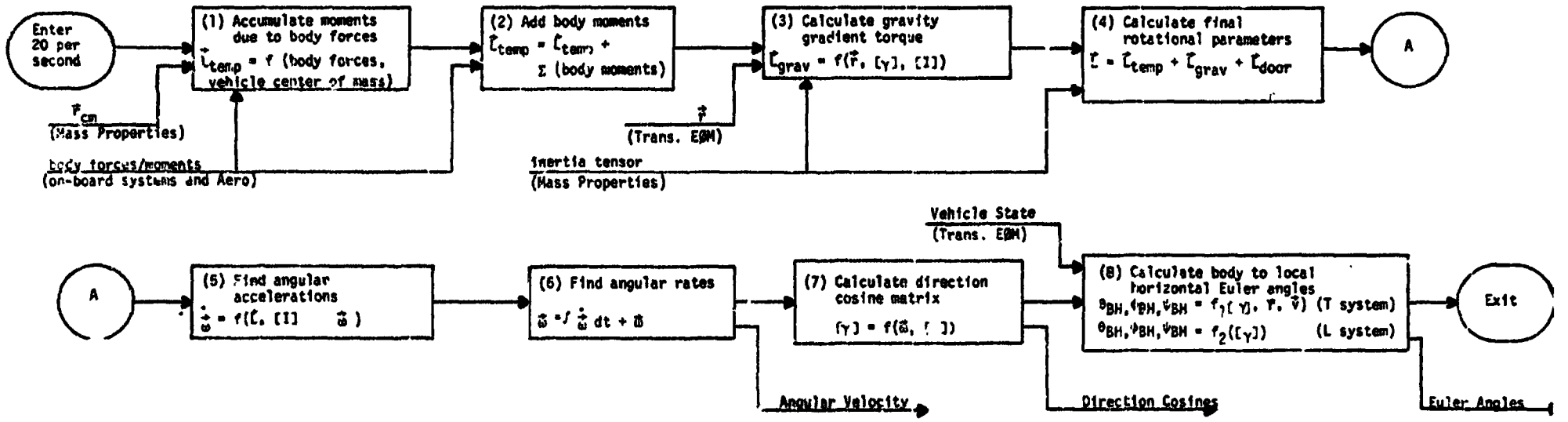

Enter 20 per second
(1) Accumulate moments due to body forces
$\dot{\vec{L}}_{temp}$ = f (body forces, vehicle center of mass)
(2) Add body moments
$\vec{L}_{temp} = \vec{L}_{temp} + \Sigma$ (body moments)
(3) Calculate gravity gradient torque
$\vec{L}_{grav} = f(\vec{r}, [\gamma], [I])$
(4) Calculate final rotational parameters
$\vec{L} = \vec{L}_{temp} + \vec{L}_{grav} + \vec{L}_{door}$
A
$\vec{r}_{cm}$ (Mass Properties)
body forces/moments (on-board systems and Aero)
$\vec{r}$ (Trans. EOM)
inertia tensor (Mass Properties)
Vehicle State (Trans. EOM)
A
(5) Find angular accelerations
$\dot{\vec{\omega}} = f(\vec{L}, [I] \quad \vec{\omega})$
(6) Find angular rates
$\vec{\omega} = \int \dot{\vec{\omega}}\, dt + \vec{\omega}$
(7) Calculate direction cosine matrix
$[\gamma] = f(\vec{\omega}, [\ ])$
(8) Calculate body to local horizontal Euler angles
$\theta_{BH}, \phi_{BH}, \psi_{BH} = f_1([\gamma], \vec{r}, \vec{v})$ (T system)
$\theta_{BH}, \psi_{BH}, \psi_{BH} = f_2([\gamma])$ (L system)
Exit
Angular Velocity
Direction Cosines
Euler Angles

FIGURE 4.3.8.1.2-1 ROTATIONAL EOM

SYMBOL DICTIONARY

$[I]$	Vehicle inertia tensor
$\vec{L}$	total body torque
$\vec{L}_{door}$	torque due to moving doors
$\vec{L}_{grav}$	gravity gradient torque
$\vec{L}_{temp}$	torque accumulator
$\vec{r}$	vehicle position
$\vec{V}$	vehicle velocity
$[\gamma]$	direction cosine matrix
θ_{BH}	local horizontal pitch
ϕ_{BH}	local horizontal roll
ψ_{BH}	local horizontal yaw
$\vec{\omega}$	angular velocity
$\dot{\vec{\omega}}$	angular acceleration

The shuttle vehicle is a complex structure composed of an aircraft, an external fuel tank, two strap-on solid rocket motors and a payload. During powered flight this structure is subjected to loads such as engine thrust, fuel slosh and aerodynamic forces. These forces cause the vehicle to bend and result in structural vibrations primarily at certain predetermined frequencies. These vibrations in turn feed into body-mounted accelerometers and rate gyros which provide the sensor data used in the vehicle control system rate-feedback and load-relief control loops. These accelerometers and rate gyros are normally placed in a vehicle in a manner to minimize the sensing of the transient effects due to bending, fuel-slosh and aeroelasticity. Filters are then added to further reduce these effects as they are seen by a control system. If these provisions are adequate to filter out these vibrational modes from the shuttle control system, it is unnecessary to simulate these dynamics in an astronaut training device, and a rigid body simulation will suffice.

The shuttle vehicle apparently will include nine rate gyro packages and six bodymounted accelerometer packages. Each rate gyro package contains three rate gyros which are mounted mutually perpendicular to one another. The accelerometer packages each contain two accelerometers. These are normally perpendicular to one another and lie in a plane perpendicular to the vehicle center-line. Each rate gyro and each accelerometer may be mounted apart from the others in its package. The inputs to these 39 sensing devices will be simulated as outputs from the bending model should flexible body dynamics be determined to be necessary.

If the bending exceeds the control system's capabilities, the following method of bending simulation is recommended. The shuttle vehicle can be idealized into a structure of rods, tubes and panels upon which

are acting the external forces mentioned above. The bending of a structure under load is the cumulative result of the bending of the individual elements composing the structure. A matrix method is recommended for the handling of the quantity of data arising in the solutions of flexure calculations of such a complex structure. This method presents data in a form suitable for use in the normal calculatory procedures of a high speed digital simulation and allows simple expansion of the program is required. The bending equations of motion for the idealized system are defined by a series of matrix multiplications where the matrices describe the thrust force, structure elements, fuel slosh effects and aerodynamic forces.

The program will be computed at a rate of at least ten times per second. Program outputs will consist of rates and accelerations sensed by the control system devices and increments to rigid body forces and moments resulting from body flexing.

The vehicle's motion can be affected by fuel slosh. The shuttle contains five reaction control system tanks in the orbiter's nose and three tanks in each of the orbital maneuvering system (OMS) engine pods. The payload bay is capable of containing up to six fuel tanks. There are four fuel tanks in the OMS pods, two per pod. The external tank consists of two main tank compartments. Neglecting the cryo tanks this accounts for 23 tanks of fuel that might need simulating.

During the first stage of flight the slosh dynamics have been estimated to be in a frequency range between 0.5 and 0.7 Hertz. During the second stage of flight this frequency is expected to be between 0.3 and 0.5 Hertz. One of the reasons slosh is critical is due to the forward location of the LO_2 tank. Slosh effects this far away from the center of

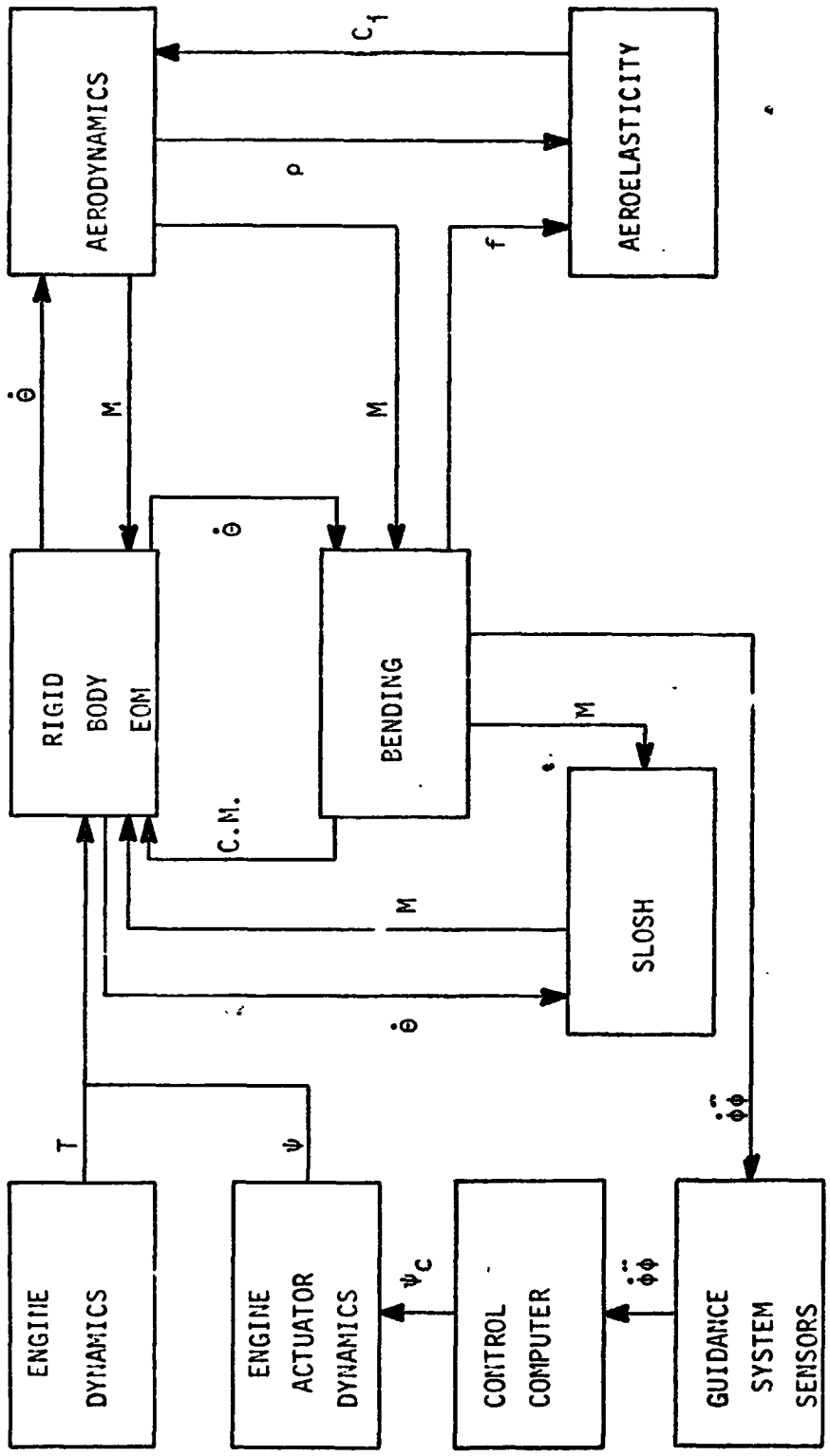
mass can have a pronounced effect on the rotational dynamics of the vehicle. The choice of which tanks must be simulated will be a function of those sloshing effects which cannot be filtered out of the control system effectively and which bending effects, which are in part a function of slosh, cannot be filtered out of the control system.

The simulation of fuel slosh may be accomplished by assuming the fuel to act similar to a spring-mass-damper system tied to the airframe and a rotatable inertia coupled to the vehicle structure through the damping action of internal baffles. The slosh model will supply the mass center vector of the fuel for each tank to the equations of motion. It will also supply the forces produced by fuel motion as the vehicle and fuel exchange momentum. Forces required by the bending model at other critical points in the vehicle will also be supplied by the fuel slosh model.

The model requires several coefficients and their interaction that will be defined as more design data becomes available. This will allow a description of the forces in each plane accounting for any cross-coupling that exists.

The slosh model program will be computed as fast as any program that uses its outputs. This is 20 times per second, the execution rate of the rotational equations of motion.

The following figure depicts a functional flow of an approach that might be used should flexible body dynamics simulation become necessary. The necessity of this simulation will be determined as the shuttle design and dynamic characteristics become better defined. Aeroelasticity simulation is discussed further in Section 4.3.8.1.4.



SLOSH, BENDING AND AEROELASTICITY

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FIGURE 4.3.8.1.2-2

It is estimated that the addition of body bending and fuel sloshing will result in the following core and time increments:

	SLOSHING	BENDING
Increase in number of executable instructions	454	4,544
Increase in number of instructions executed per second	163,440	272,640
Increase in data pool	1,350	2,250

4.3.8.1.3 Mass Properties

The shuttle vehicle mass properties simulation must calculate the current vehicle mass, center of mass, and inertial tensor for the vehicle equations of motion. Mass properties will be calculated in the B coordinate system. In order to accomplish this, the mass properties simulation obtains information on mass and mass distribution of on-board consumables from the simulated vehicle systems, and on vehicle configuration from the environmental control system, payload accommodation system, simulated docking system, simulated SRM's, and simulated external tank. The mass properties simulation accepts the following specific dynamic inputs:

	Consumables		
	Mass	Center of Mass	Inertial Tensor (about own C.M.)
MPS Fuel/Oxidizer	X	X	X
SRM Fuel	X	X	X
RCS Propellant	X	X	
OMS Fuel/Oxidizer	X	X	X
APPS Fuel	X	X	X
APU Fuel	X	X	
Cryogenics Reactant	X		
Water	X		
GN_2	X		

	Configuration
SRM's	Attachment boolean
External tank	Attachment boolean
Payload Doors	Center of mass, inertia tensor about own C.M.
Space Radiators	Center of mass, inertia tensor about own C.M.
Payload Manipulator	Center of mass, inertia tensor about own C.M.
	Target Vehicles
Each target vehicle	Attachment/docked status, mass, center of mass (shuttle body coordinates), inertia tensor about own C.M.

Other consumable or configuration changes are not expected to be of sufficient magnitude to warrant simulation. The simulated mass properties must be updated ten times per second during boost. At other times, however, mass flows are sufficiently low to permit slower iteration rates. With approximate OMS mass flow of .5 $\frac{\text{slug}}{\text{sec}}$ per engine, ABPS mass flow of .6 $\frac{\text{slug}}{\text{sec}}$, and RCS mass flow of .15 $\frac{\text{slug}}{\text{sec}}$ per jet, an update rate of once per two seconds should be feasible. However, to correctly simulate docking/payload attachment effects, must faster response is required. Whenever any change in docking or attachment status takes place, its effect should be reflected as soon as possible in vehicle mass properties. Thus, in orbit, the portion of the program which handles docked/attached configurations is updated ten times per second. The conceptual design is illustrated in figure 4.3.8.1.3-1.

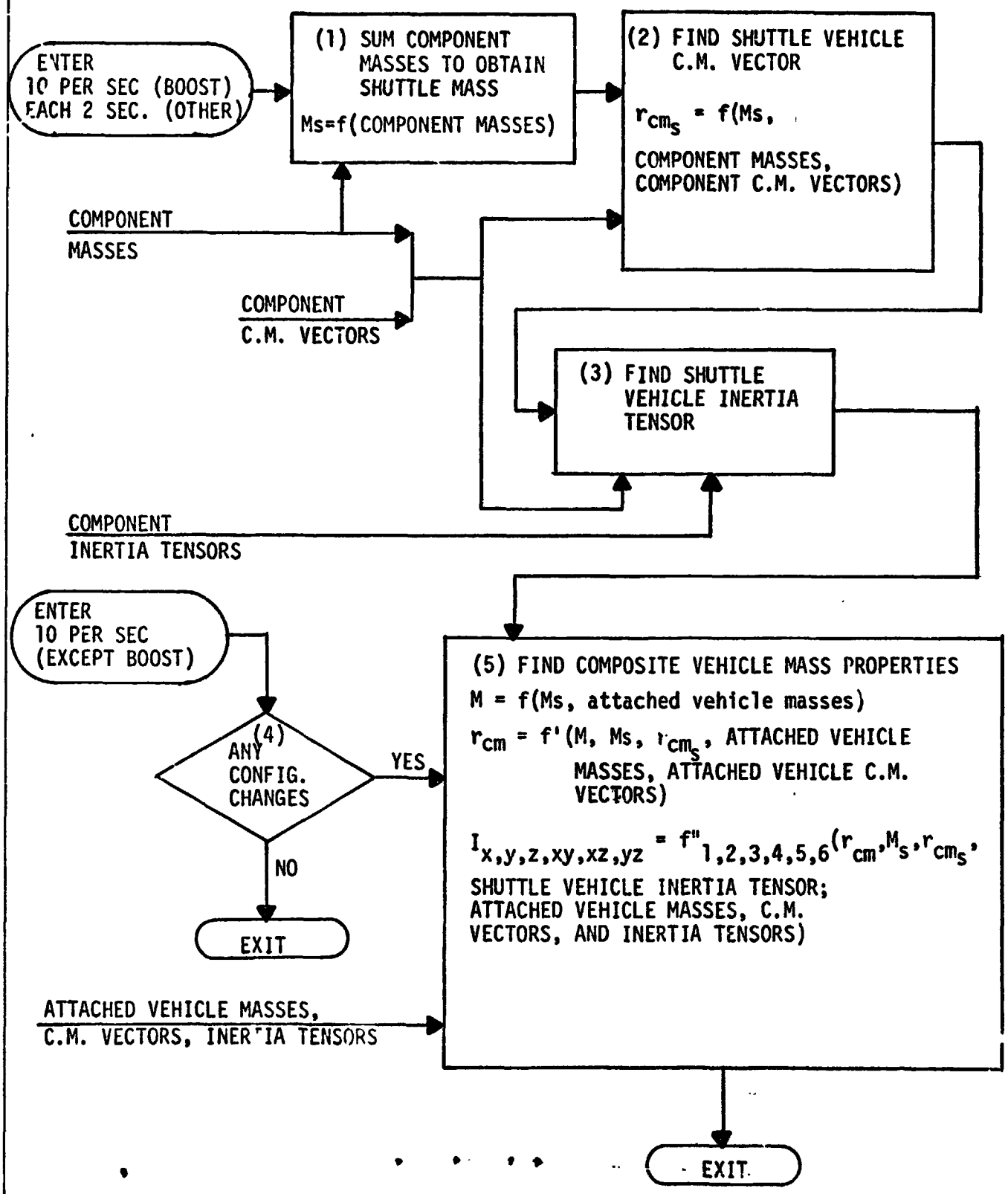
ENTER
10 PER SEC (BOOST)
EACH 2 SEC. (OTHER)
(1) SUM COMPONENT MASSES TO OBTAIN SHUTTLE MASS
Ms=f(COMPONENT MASSES)
(2) FIND SHUTTLE VEHICLE C.M. VECTOR
r_{cm_s} = f(Ms, COMPONENT MASSES, COMPONENT C.M. VECTORS)
COMPONENT MASSES
COMPONENT C.M. VECTORS
(3) FIND SHUTTLE VEHICLE INERTIA TENSOR
COMPONENT INERTIA TENSORS
ENTER
10 PER SEC
(EXCEPT BOOST)
(4) ANY CONFIG. CHANGES
YES
NO
EXIT
(5) FIND COMPOSITE VEHICLE MASS PROPERTIES
M = f(Ms, attached vehicle masses)
r_{cm} = f'(M, Ms, r_{cm_s}, ATTACHED VEHICLE MASSES, ATTACHED VEHICLE C.M. VECTORS)
$I_{x,y,z,xy,xz,yz}$ = f"1,2,3,4,5,6(r_{cm},M_s,r_{cm_s}, SHUTTLE VEHICLE INERTIA TENSOR; ATTACHED VEHICLE MASSES, C.M. VECTORS, AND INERTIA TENSORS)
ATTACHED VEHICLE MASSES, C.M. VECTORS, INERTIA TENSORS
EXIT

FIGURE 4.3.8.1.3-1

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Symbol Dictionary for Figure 4.3.8.1.3-1

I_x	cluster x-axis moment of inertia	M	total cluster mass
I_y	cluster y-axis moment of inertia	Ms	shuttle vehicle mass (exclusive of payloads)
I_z	cluster z-axis moment of inertia	$\vec{r}_{cm}$	cluster C.M. position vector (body coordinates)
I_{xy}	cluster x-y product of inertia	$\vec{r}_{cm_s}$	shuttle vehicle C.M. position (exclusive of payloads)
I_{yz}	cluster y-z product of inertia		

The consumable masses will be added to the vehicle dry mass, a reset constant, to obtain M_s. Then, $\vec{r}_{cm_s}$ will be calculated using the consumable masses and mass centers, masses and mass centers of configuration changeable portions, and the mass and mass center of the remainder of the vehicle. Consumable mass centers not specified above as calculated dynamically will be represented by reset constants. Shuttle vehicle inertia tensor (less payloads) will be calculated using the component masses, mass centers, and inertia tensors specified above (except for target vehicles), as well as mass properties of the remainder of the vehicle. When a component's inertia tensor is not specified above as calculated dynamically, it will be assumed that all its mass is concentrated at its mass center. Once shuttle vehicle (less payload) mass properties are found, they are then combined with mass properties of attached payloads to obtain cluster mass properties.

4.3.8.1.4 Aerodynamics

The simulated shuttle vehicle aerodynamics provides forces and moments due to vehicle motion through the atmosphere to the shuttle vehicle equations of motion. Inputs to the simulated aerodynamics include vehicle position, velocity, altitude, and altitude rate (from translational EØM); direction cosine matrix and angular velocity (from rotational EOM); aerosurface deflections (from Aerosurface control); proximity aerodynamic effects (from target vehicle aeroflight aerodynamics); pilot barometric correction setting (from the crew station); and wind velocity/azimuth, gust settings, sea level temperature, and barometric pressure setting (from instructor station). Outputs include aerodynamic force and moment (both in the B coordinate system), ambient and dynamic pressure, true and indicated airspeed, indicated altitude, ambient outside air temperature, and angles of attack and sideslip. Vehicle position and velocity will be used to calculate velocity with respect to rotating atmosphere (taking due account of the current EØM coordinate system). Wind and rough air effects are then included to obtain velocity with respect to the moving atmosphere, which is then rotated to the B coordinate system. A prestored wind profile (velocity and azimuth) will be utilized, with instructor override capability. During spaceflight missions, provision will be made for differing wind profiles for boost and entry. During boost, orbit, and high-altitude phases of entry, nominal profiles of atmospheric density, temperature, and pressure versus altitude will be used. During low-altitude phases of entry, and during ferry flights, instructor control over atmospheric conditions will be provided through variable settings of sea level temperature and barometric pressure. In this regime, simulation of atmospheric properties will be based on pressure-altitude. During re-entry, delta-effects due to instructor settings will be gradually included below a specific altitude, until they are fully effective at a lower altitude, in order to provide smooth

transition. Separate calculations of aerodynamic forces and moments are provided for each of the three principal configurations present during space missions, namely, orbiter + tank + SRM's (first stage), orbiter + tank (second stage), and orbiter alone. Orbiter alone calculations will be capable of simulating both the space mission and ferry mission configuration aerodynamic properties. Aerodynamic forces and moments will be computed in the B-coordinate system for both boost configurations and in stability axes during orbiter-alone configuration. Stability axis forces and moments will be transformed to the B-coordinate system before exiting the program. Aerodynamic coefficients will be simulated using combinations of functions of one, two, and/or three variables, constants, and mathematical expressions. The effects of vehicle elasticity on vehicle aerodynamics will be simulated in the conventional manner by introducing aeroelastic corrections into the aerodynamic equations. The general approach will be to generate aerodynamic characteristics of a "clean" aircraft in cruise status. Incremental effects of aerosurfaces, ground or target vehicle proximity, etc. will then be combined with the above to obtain all-condition performance simulation. Prime aerodynamic parameters will be simulated to extended values of angle-of-attack and sideslip to afford reasonable stalling characteristics. Definition of parameters upon which aerodynamic coefficients will be dependent was generally obtained from currently existing design data, which is incomplete. As additional data becomes available, parameter dependencies below should be reviewed and revised accordingly. During orbital phases, effects upon aerodynamic forces of aerosurface deflections will not be simulated. A high aerodynamics iteration rate during entry and ferry is desirable for proper simulation of higher frequency effects within pilot perception. A rate of 20 per second should be quite adequate to accomplish this. Current Saturn boost simulations have run successfully with aerodynamics update rates of 10 per second. However, the period during the max-q

region in which aerosurface control is used on the shuttle may render desirable a higher update rate. Thus, at this time, a 20 per second rate is specified for boost as well. During orbital phases, aero effects are noticeable only after extended periods of time, and body rates (and therefore relative wind) do not change rapidly except over brief periods of time. Thus, an update rate of twice per second should be quite adequate in this phase. The aerodynamics conceptual design is sketched in Figure 4.3.8.1.4-1.

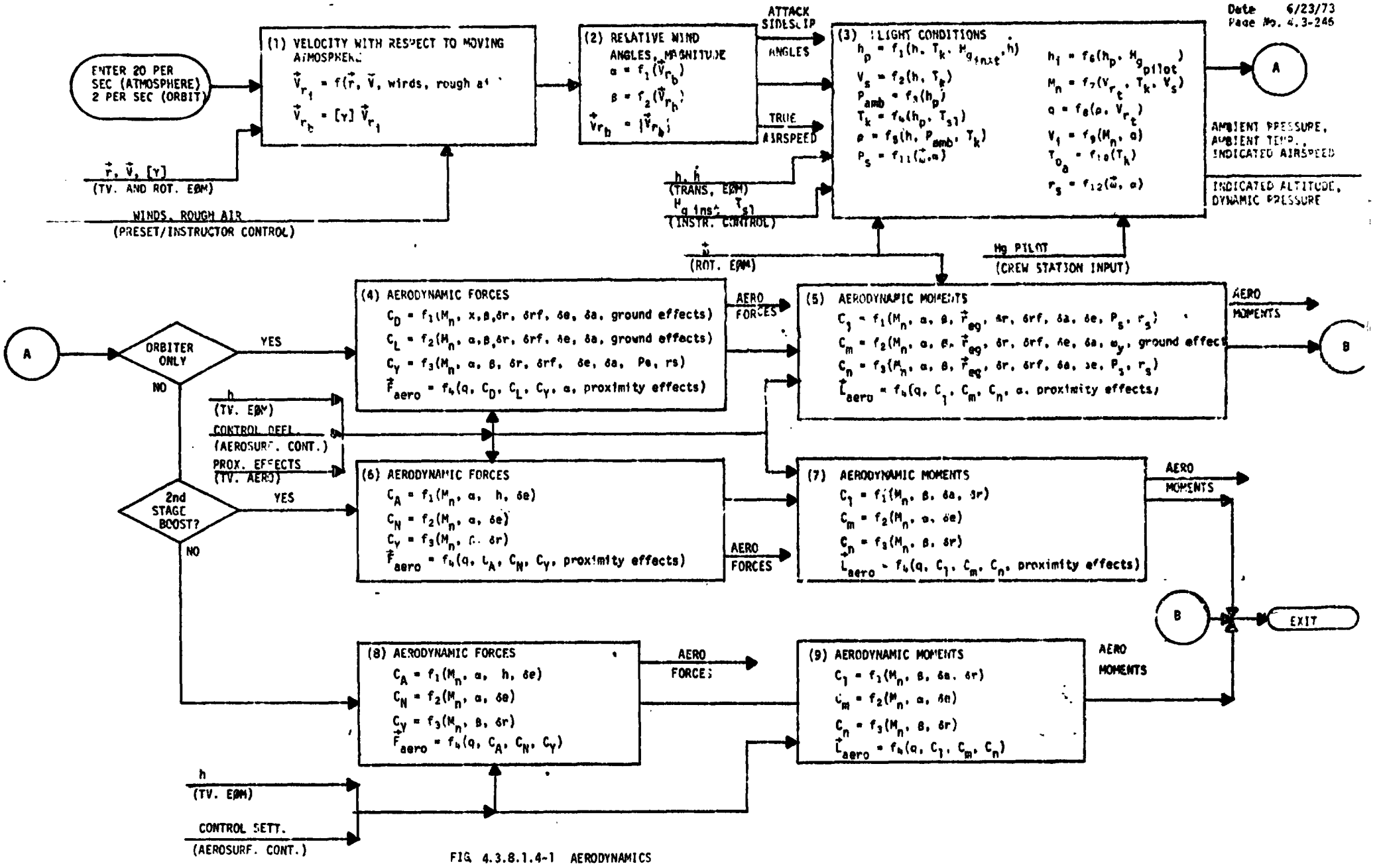

ENTER 20 PER SEC (ATMOSPHERE) 2 PER SEC (ORBIT)
(1) VELOCITY WITH RESPECT TO MOVING ATMOSPHERE
$\vec{V}_{r_t} = f(\vec{r}, \vec{V}$, winds, rough air
$\vec{V}_{r_b} = [\gamma]\,\vec{V}_{r_t}$
$\vec{r}, \vec{V}, [\gamma]$
(TV. AND ROT. EØM)
WINDS, ROUGH AIR
(PRESET/INSTRUCTOR CONTROL)
(2) RELATIVE WIND ANGLES, MAGNITUDE
$\alpha = f_1(\vec{V}_{r_b})$
$\beta = f_2(\vec{V}_{r_b})$
$\dot{V}_{r_b} = |\vec{V}_{r_b}|$
ATTACK
SIDESLIP
ANGLES
TRUE AIRSPEED
(3) FLIGHT CONDITIONS
$h_p = f_1(h, T_k, M_{g_{instr}}, \dot{h})$
$V_s = f_2(h, T_k)$
$P_{amb} = f_3(h_p)$
$T_k = f_4(h_p, T_{s1})$
$\rho = f_5(h, P_{amb}, T_k)$
$P_s = f_{11}(\vec{\omega}, \alpha)$
$h_i = f_6(h_p, M_{g_{pilot}})$
$M_n = f_7(V_{r_t}, T_k, V_s)$
$q = f_8(\rho, V_{r_t})$
$V_i = f_9(M_n, \alpha)$
$T_{o_a} = f_{10}(T_k)$
$r_s = f_{12}(\vec{\omega}, \alpha)$
h, ḣ
(TRANS. EØM)
$M_{g_{instr}}$, T_{s1}
(INSTR. CONTROL)
$\vec{\omega}$
(ROT. EØM)
$M_{g_{PILOT}}$
(CREW STATION INPUT)
A
AMBIENT PRESSURE, AMBIENT TEMP., INDICATED AIRSPEED
INDICATED ALTITUDE, DYNAMIC PRESSURE
A
ORBITER ONLY
YES
NO
(4) AERODYNAMIC FORCES
$C_D = f_1(M_n, \alpha, \beta, \delta r, \delta rf, \delta e, \delta a$, ground effects)
$C_L = f_2(M_n, \alpha, \beta, \delta r, \delta rf, \delta e, \delta a$, ground effects)
$C_Y = f_3(M_n, \alpha, \beta, \delta r, \delta rf, \delta e, \delta a, P_s, r_s)$
$\vec{F}_{aero} = f_4(q, C_D, C_L, C_Y, \alpha$, proximity effects)
AERO FORCES
(5) AERODYNAMIC MOMENTS
$C_l = f_1(M_n, \alpha, \beta, \vec{r}_{eg}, \delta r, \delta rf, \delta a, \delta e, P_s, r_s)$
$C_m = f_2(M_n, \alpha, \beta, \vec{r}_{eg}, \delta r, \delta rf, \delta e, \delta a, \omega_y$, ground effect
$C_n = f_3(M_n, \alpha, \beta, \vec{r}_{eg}, \delta r, \delta rf, \delta a, \delta e, P_s, r_s)$
$\vec{L}_{aero} = f_4(q, C_l, C_m, C_n, \alpha$, proximity effects)
AERO MOMENTS
B
h
(TV. EØM)
CONTROL DEFL.
(AEROSURF. CONT.)
PROX. EFFECTS
(TV. AERO)
2nd STAGE BOOST?
YES
NO
(6) AERODYNAMIC FORCES
$C_A = f_1(M_n, \alpha, h, \delta e)$
$C_N = f_2(M_n, \alpha, \delta e)$
$C_Y = f_3(M_n, \beta, \delta r)$
$\vec{F}_{aero} = f_4(q, C_A, C_N, C_Y$, proximity effects)
AERO FORCES
(7) AERODYNAMIC MOMENTS
$C_l = f_1(M_n, \beta, \delta a, \delta r)$
$C_m = f_2(M_n, \alpha, \delta e)$
$C_n = f_3(M_n, \beta, \delta r)$
$\vec{L}_{aero} = f_4(q, C_l, C_m, C_n$, proximity effects)
AERO MOMENTS
B
EXIT
(8) AERODYNAMIC FORCES
$C_A = f_1(M_n, \alpha, h, \delta e)$
$C_N = f_2(M_n, \alpha, \delta e)$
$C_Y = f_3(M_n, \beta, \delta r)$
$\vec{F}_{aero} = f_4(q, C_A, C_N, C_Y)$
AERO FORCES
(9) AERODYNAMIC MOMENTS
$C_l = f_1(M_n, \beta, \delta a, \delta r)$
$C_m = f_2(M_n, \alpha, \delta e)$
$C_n = f_3(M_n, \beta, \delta r)$
$\vec{L}_{aero} = f_4(q, C_l, C_m, C_n)$
AERO MOMENTS
h
(TV. EØM)
CONTROL SETT.
(AEROSURF. CONT.)

FIG. 4.3.8.1.4-1 AERODYNAMICS

SYMBOL DICTIONARY FOR FIGURE 4.3.8.1.4

C_A	axial force coefficient
C_D	drag coefficient
C_L	hft coefficient
C_l	rolling moment coefficient
C_m	pitching moment coefficient
C_N	normal force coefficient
C_n	yawing moment coefficient
C_y	side force coefficient
$\vec{F}_{aero}$	total aerodynamic force
h	altitude
$\dot{h}$	altitude rate
Hg_{inst}	instructor baro setting
Hg_{pilot}	pilot baro correction
h_i	indicated altitude
h_p	pressure altitude
$\vec{L}_{aero}$	total aerodynamic moment
M_n	mach number
P_{amb}	ambient pressure
P_s	stability axis roll rate
q	dynamic pressure
$\vec{r}$	vehicle position
r_s	stability axis yaw rate
T_k	absolute air temperature
$T_{ØA}$	outside air temperature
T_{SL}	sea level temperature
$\vec{V}$	vehicle velocity
V_i	indicated airspeed
$\vec{V}_{rb}$	velocity with respect to moving atmosphere (B coordinate system)
$\vec{V}_{ri}$	velocity with respect to moving atmosphere (EØM coordinate system)
V_{rt}	true airspeed
V_s	speed of sound
α	angle of attack
β	sideslip angle
$[\gamma]$	direction cosine matrix
δ_a	aileron (differential elevon) defletion
δ_e	elevon deflection
δ_r	rudder deflection
δ_{rf}	rudder flare
ρ	atmospheric density
$\vec{\omega}$	vehicle angular velocity
ω_y	vehicle body-axis pitch rate

Aeroelastic effects due to structural bending and torsion will be simulated should it become necessary to include flexible body dynamics in the shuttle simulation. The basic design structure of the system would apply additions and corrections to the non-dimensional stability coefficients in the vehicle aerodynamics program.

Aeroelastic effects will be simulated during a mated ascent, staging, entry/transition and cruise/landing operations. These effects can arise during these operations from any of the following:

1. Wing torsion and bending due to:
   a. airloads in equilibrium flight,
   b. differential elevon deflection,
   c. "dead weight" distribution when the vehicle is subjected to a normal acceleration, and
   d. elevon deflection.
2. Vertical tail torsion and bending due to rudder deflection.
3. Fuselage bending and torsion due to airloads on the vertical tail.
4. Fuselage bending due to "dead weight" distribution when the vehicle is subjected to a normal acceleration.

The magnitude of these simulated effects for any particular vehicle configuration of a particular flight condition is dependent on the following factors.

1. Dynamic pressure.
2. Airframe configuration.
3. Mach number.
4. Normal acceleration.

Aeroelastic effects are primarily a function of dynamic pressure, q. By definition, $q = .5\rho V^2$, where ρ is the density of air and V is the true forward velocity. Since ρ decreases as altitude increases it is clear that q increases as Mach No. increases and altitude decreases. If it is assumed that aeroelastic effects increase with q, then it can be concluded that the magnitude of aeroelastic effects are largest when the vehicle is at high speed and low altitude.

The magnitude and more importantly, the sign of aeroelastic corrections to the rigid body stability coefficients depends to a large extent upon the configuration of the vehicle. In the case of shuttle, the overall configuration will change from launch to landing.

In addition to determining the effect of dynamic pressure, the flight Mach. No. is important in determining corrections to the stability coefficients. Since the distribution of air loads is altered as the Mach No. is changed, the resulting aeroelastic deflections are also affected and are especially critical in the transonic region.

Depending on the particular vehicle configuration, aeroelastic effects can be important under flight conditions involving normal accelerations other than one "g". When the vehicle is subjected to accelerations the dead weight of the body produces both torsional and bending deflections. The correct method for introducing these effects into the dynamics of the body is to provide equations of motion to account for the elastic degrees of freedom. However, if the motion of the airframe are assumed to be slow with respect to the elastic frame, the inertial effects of various concentrated masses relative to the entire mass can be neglected. It may be concluded that for a stabilized normal acceleration no additional equations of motion are

required and aeroelastic effects may be taken into account by additions and corrections to the conventional equations of motion.

The conceptual design for aeroelastic simulation as illustrated in Figure 4.3.8.1.4-2 takes into account the four factors described and treats them as separate program models. To accurately simulate the effects due to dynamic pressure, airframe configuration, Mach No. and normal acceleration, shuttle data on aeroelastic response must be available prior to implementation.

In addition to the four models containing response data, a control program is required to read the data, interpolate, and output coefficient corrections at a compatible simulation rate.

Coefficients important to vehicle stability and control and most likely to be affected by aeroelasticity are: Cm_{α}, $Cm_{\dot{\alpha}}$, $Cm_{\delta e}$, Cm_{q}, CL_{α}, $CL_{\delta a}$, CL_{ρ}, $Cm_{\delta a}$, Cl_{β}, and $Cm_{\delta r}$.

It is estimated that the addition of the above described aeroelastic simulation will result in an increase of 3,000 executable instructions in core, a timing increment of 192,000 instructions per second, and a data pool increment of 1,200 values.

In addition to the aeroelastic simulation model, the characteristic properties of flutter may be required. Flutter involves aerodynamic forces, inertia forces and the elastic properties of a surface. The distribution of mass and stiffness in a structure determine certain natural frequencies and modes of vibration. If the structure is subject to a forcing frequency near these natural frequencies, a resonant condition can result with unstable oscillations.

The characteristic effects of flutter shall be simulated in the same manner as the aeroelastic model, i.e., additions and corrections to the aerodynamic equations of motion. These effects normally occur above the limit speed (red-line speed) of the vehicle. However, if excessive play and flexibility exist, flutter can occur below the limit airspeed.

It is estimated that the addition of flutter simulation will result in an increase of 1,000 executable instructions in core, a timing increment of 48,000 instructions per second, and a data pool increment of 800 values.

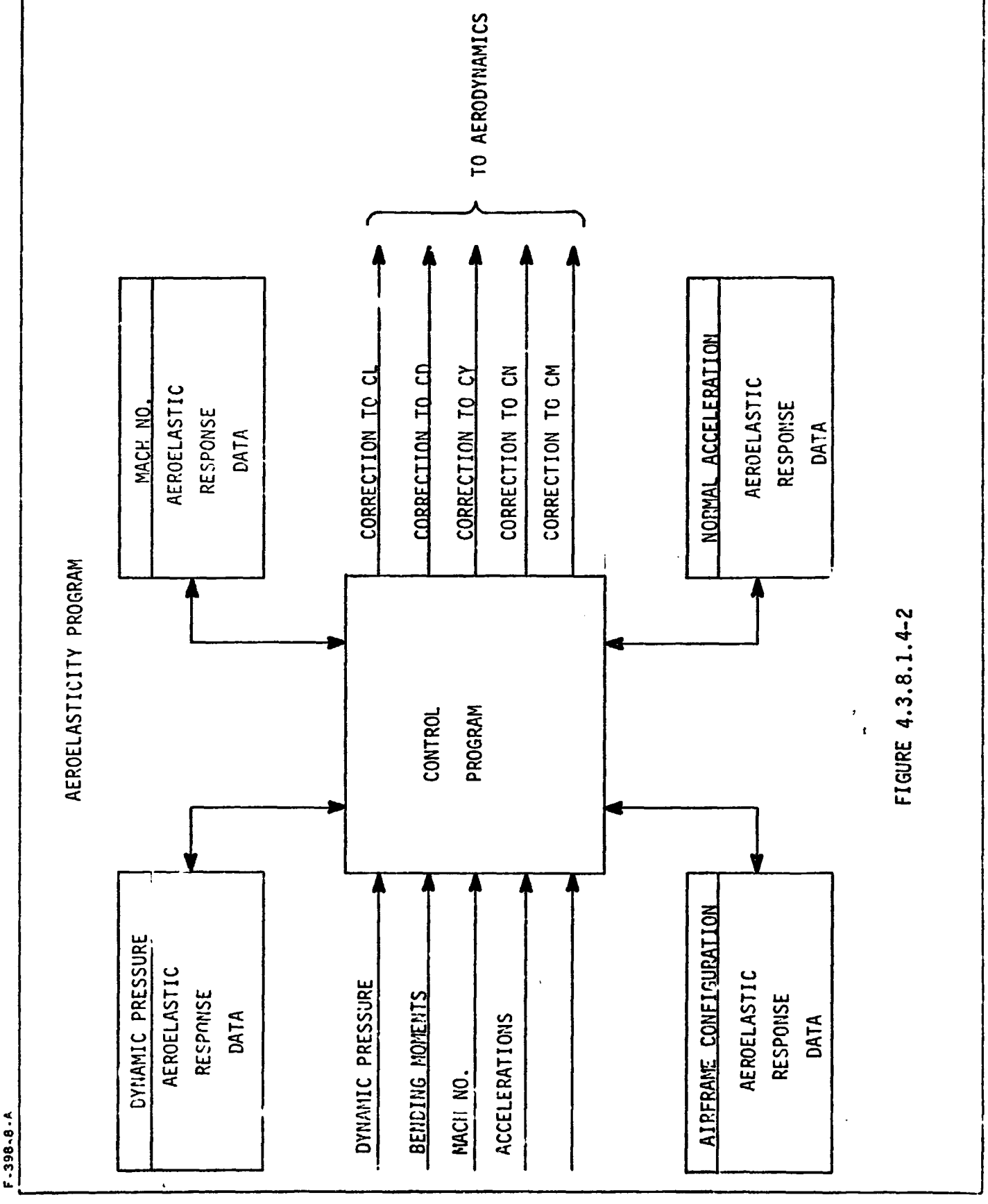


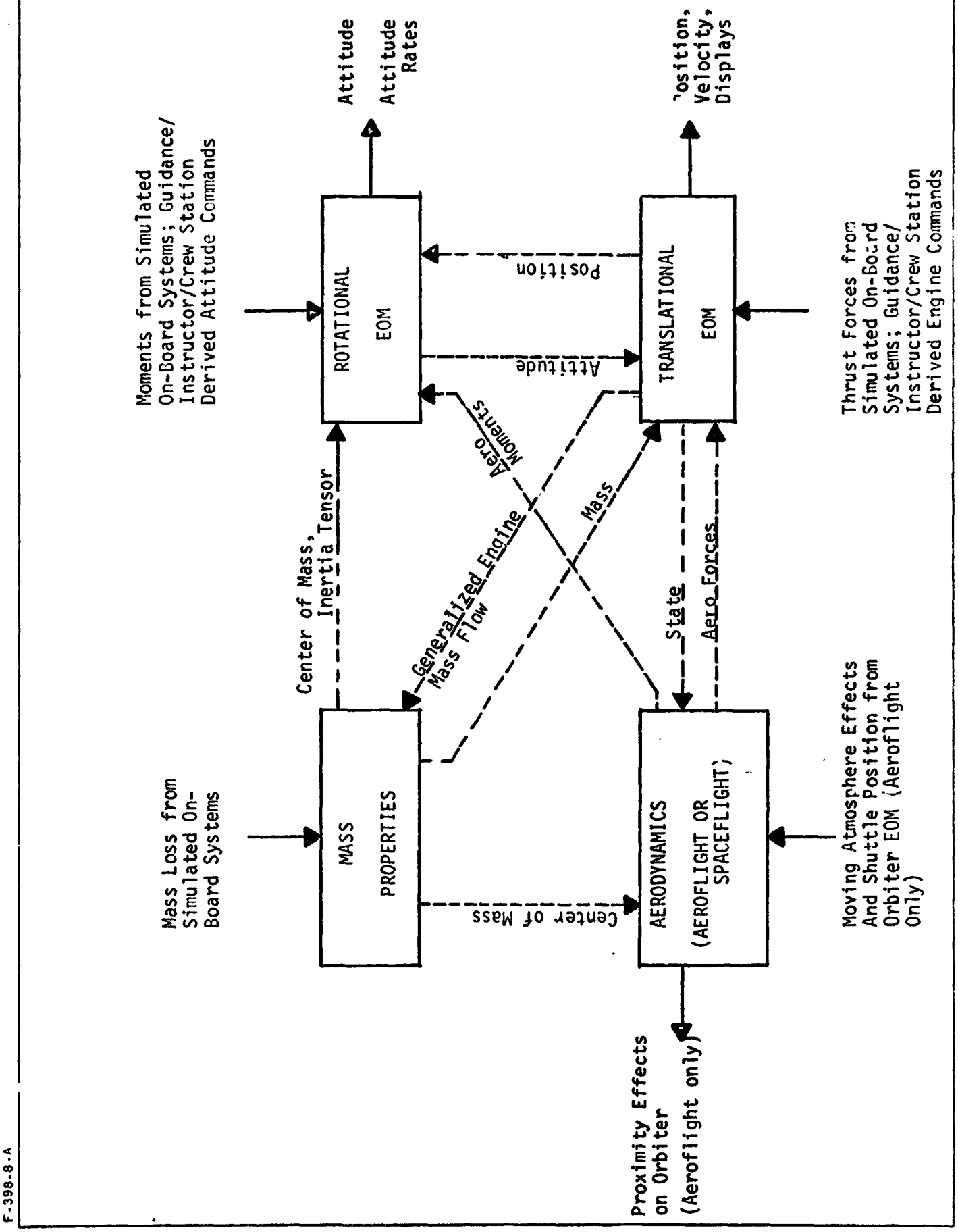
FIGURE 4.3.8.1.4-2

4.3.8.2 Target Vehicles

The target vehicle equations of motion will simulate translational and rotational dynamics for up to eight different target vehicles. The same basic logic will be used for each of the eight target vehicles, and is discussed below. The equations of motion will provide generalized simulations of rotational/translational propulsion systems, which may optionally be used for a given payload. Alternately, the equations of motion will be able to pick up rotational moments, translational forces, and mass flow from specialized payload simulation programs. The generalized propulsion systems will be configured to accept inputs from simulated generalized target vehicle guidance, or from either the instructor or simulated shuttle vehicle. Generalized propulsion and control simulations are used for the reasons stated in the rationale to the Shuttle Mission Simulator Requirements Report. To summarize some of the reasons, some target vehicle dynamics simulation will be required, especially during rendezvous and docking. Since the target vehicle may be active during part of rendezvous, and may control its own attitude during station-keeping, some simulation of related on-board systems needs to be present in these cases. To check out the initial simulator fully, some such simulation should be present in the initial simulator. It should not require greatly increased effort to insert the above generalized simulations rather than a simulation of a particular target vehicle. It should further vastly reduce the otherwise considerable effort required to update the simulator to an alternate target vehicle. Provision will be made to initialize each individual target vehicle simulation either upon release from the shuttle vehicle (or its payload manipulator), from shuttle (or manipulator) dynamics data, or at a preset time with a preset translational and rotational state vector. Provision will be made to terminate each individual target vehicle simulation as a function of

distance from the shuttle vehicle, which distance may be different for each individual target vehicle. Provision will be made to permit two different termination distances for the external tank, one for dynamic pressure at separation less than 2 lb/ft^2 and the other for larger dynamic pressures. Termination distances and initialization option (and initial state and time for the preset initialization option) will be determined by reset terms. The conceptual design for target vehicle equations of motion has been subdivided into five subsystems, interrelated as shown below. For a given vehicle, either aeroflight aerodynamics or spaceflight aerodynamics will be executed, but not both. Aeroflight aerodynamics will be executed for SRM's and external tank, while spaceflight aerodynamics will be executed for all other target vehicles.

DATE 6/23/73	THE SINGER COMPANY SIMULATION PRODUCTS DIVISION	PAGE NO. 4.3-254
REV.	BINGHAMTON, NEW YORK	REP. NO.



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4.3.8.2.1 Translational EOM and Propulsion

The simulated target vehicle translational equations of motion maintain target vehicle or payload c. m. positions and velocities when not attached to the shuttle vehicle or manipulator. Inputs to the equations of motion are thrust force, aerodynamic forces, docking mechanism forces, and vehicle mass. Vehicle mass is obtained from simulated target vehicle mass properties, and aerodynamic forces from simulated target vehicle aerodynamics. Thrust force may be obtained either from a specific target vehicle propulsion system simulation program or from a generalized approximate thrust simulation located within the translational EOM program. Any specific target vehicle propulsion system simulation program will be added later by modification (excepting boost SRM's and external tank), and will not form a part of the delivered simulator. The translational EOM program will, however, contain the necessary interface to permit addition of such a specific program without modification to translational EOM. The generalized thrust approximator will form a part of the initial simulator. A reset boolean will be provided to bypass the routine (it is bypassed if no translational propulsion system exists on a target vehicle, or if the propulsion system is simulated elsewhere in detail). Thrust and associated mass flow rate will be obtained by reset constants when the engine(s) fire, and will be zero at other times. Engine firing times and durations will be obtained from the simulated generalized target vehicle guidance, with instructor override provided. Thrust force from the generalized engine will always act along the body longitudinal axis and directly through the vehicle mass center. Body forces will be summed, transformed to the T system, and divided by mass to obtain accelerations. Two integration loops will be provided which calculate gravity and integrate total acceleration to obtain velocity and position. The loop in use at a given time is determined on the basis of the current magnitude of body acceleration. Above the threshold acceleration magnitude, the high-speed loop is used,

below it, the low-speed loop is used. The high-speed loop will be esstantially the same as the non-orbit loop in shuttle translational EOM and the low-speed loop will be essentially the same as the orbit loop in shuttle translational EOM. The descriptions and explanations concerning these loops in section 4.3.8.1.1 apply here as well. A number of parameters are then generated for display purposes, including

orbital elements

shuttle - target vehicle range

shuttle - target vehicle range rate

target vehicle azimuth and elevation (from shuttle)

For atmospheric target vehicles (SRM's, external tank), a check will be made for recontact. For this purpose, the shuttle fuselage will be approximated as a rectangular solid, and wings and vertical stabilizer by infinitely thin planar surfaces. The target vehicle will be approximated as a cylindrical solid. Target vehicle translational state will be updated 10 times each second. During powered flight, this rate should provide adequate accuracy. During coasting orbital flight, the iteration rate of the extrapolation portion of the integration scheme has practically no influence on accuracy. This rate should, however, be adequate to prevent noticeable jumps in relative state. During sten-ahead mode, the approach used for shuttle state advancement described in section 4.3.8.1.1 will also be used for target vehicle state advancement. The conceptual design for target vehicle translational EOM is sketched in figure 4.3.8.2.1-1.

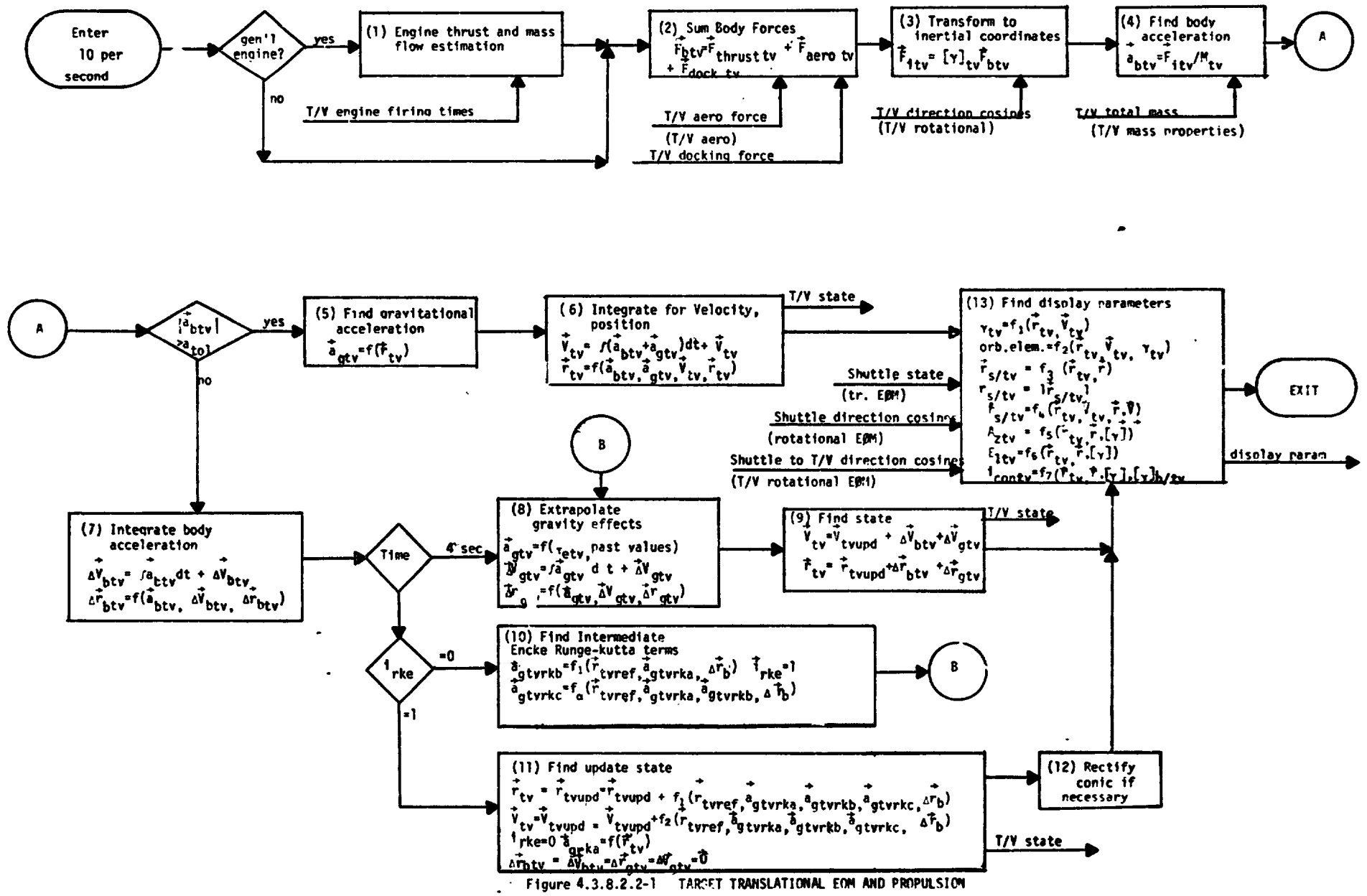


Figure 4.3.8.2.2-1 TARGET TRANSLATIONAL EOM AND PROPULSION

Symbol Dictionary for Figure 4.3.8.2.1-1

$\vec{a}_{btv}$	target vehicle body acceleration
$\vec{a}_{gtv}$	target vehicle gravitational acceleration
$\vec{a}_{gtvrka}$	intermediate gravitational acceleration
$\vec{a}_{gtvrkb}$	intermediate gravitational acceleration
$\vec{a}_{gtvrkc}$	intermediate gravitational acceleration
a_{tol}	low speed loop acceleration tolerance
A_{ztv}	target vehicle azimuth with respect to shuttle body
E_{ltv}	target vehicle elevation angle with respect to shuttle body
$\vec{F}_{aero_{tv}}$	aerodynamic force on target vehicle
$\vec{F}_{b_{tv}}$	total body force on target vehicle (TV body coordinate)
$\vec{F}_{dock_{tv}}$	docking force on target vehicle
$\vec{F}_{i_{tv}}$	total body force on target
$\vec{F}_{thrust_{tv}}$	thrust force on target vehicle
$i_{con_{tv}}$	flag indicating tv contact with shuttle vehicle
i_{RKE}	Runge-Kutta logic flag
M_{tv}	total target vehicle mass
$\vec{r}$	shuttle position
$r_{s/tv}$	target vehicle range
$\vec{r}_{s/tv}$	vector from shuttle to target vehicle
$\vec{r}_{tv}$	target vehicle position
$\vec{r}_{tv_{ref}}$	Encke reference position
$\vec{r}_{tv_{upd}}$	target vehicle position at last low speed loop update
$\dot{r}_{s/tv}$	target vehicle range rate
$\vec{v}$	shuttle velocity
$\vec{v}_{tv}$	target vehicle velocity
$\vec{V}_{tv_{upd}}$	target vehicle velocity at last low speed loop update
γ_{tv}	target vehicle flight path angle
$[\gamma]$	shuttle attitude direction cosines
$[\gamma]_{B/tv}$	shuttle body to target vehicle body direction cosines
$[\gamma]_{tv}$	target vehicle attitude direction cosines
$\vec{\Delta r}_{btv}$	delta position due to body acceleration since last update
$\vec{\Delta r}_{gtv}$	delta position due to gravitational acceleration since last update
$\vec{\Delta V}_{btv}$	delta velocity due to body acceleration since last update
$\vec{\Delta V}_{gtv}$	delta velocity due to gravitational acceleration since last update
T_{ETV}	time since last low speed loop update

4.3.8.2.2 Rotational EOM and Attitude Control

The simulated target vehicle rotational equations of motion maintain target vehicle or payload attitudes and attitude rates when not attached to the shuttle vehicle or manipulator. Inputs to the equations of motion are attitude control moments, thrust moments, aerodynamic moments, moments exerted by the docking mechanism, and vehicle mass center and inertia properties. Mass center and inertia properties are obtained from simulated target vehicle mass properties, and aerodynamic moments from simulated target vehicle aerodynamics. Attitude control moments may be obtained either from a specific target vehicle control system simulation program, or from a generalized approximate control logic and thruster simulation located within the rotational EOM program. Any specific target vehicle control system simulation will be added later by modification, and will not form a part of the initial simulator. Target vehicle rotational EOM will, however, contain the necessary interface provisions to permit addition of such a specific program without modification to rotational EOM. The generalized approximate control logic and thruster simulation will form a part of the initial simulator. A reset boolean will be provided to bypass this routine (it is bypassed if no attitude control system exists on the vehicle or the attitude control system is simulated elsewhere in detail). Attitude commands will be obtained from simulated target vehicle guidance, the shuttle vehicle, or the instructor. Peset terms will be used to approximate the control phase plane logic. The phase plane will be assumed to be symmetric with respect to positive or negative rates, and identical for all three body axes. Up to five segments (linear or quadratic) may be used to define the upper deadband limits, and up to four may be used for the lower deadband limit. Up to five rate command regions may be defined in the upper region outside the deadband; up to two regions in the lower. Linear or quadratic segments may be used to separate these regions. The rate command in each region may be expressed as

a first-order function of rate and position error. Only as many segments and regions as needed must be used. Segments bounding region and the deadband, as well as formulae for commanded rate change in each region will be defined by reset constants. Total reaction control moment about each axis will also be defined by reset constants. The above generalized phase plane logic will be capable of simulating the nominal shuttle orbiter phase plane; the only approximations required being of the formulae for the commanded rate changes in two of the seven firing regions. Target vehicles controlled by CMG's characteristically possess very slow attitude response. It is expected that any CMG controlled payloads will not exhibit substantial attitude change during the probably brief period in which they are in close visual contact with the shuttle. Their attitudes should remain inertially fixed. Thus, provision is made to bypass rotational EOM entirely for such payloads, providing an inertially fixed attitude. In a case in which better simulation is required, a modification can, of course, be readily added. Reaction control moments will be added to aerodynamic moments and thrust moments (from any special simulation - the generalized engine in translational EOM generates no torque). Gravity gradient moments will be calculated and included. Euler's equations will be solved to obtain angular accelerations, which will be integrated to obtain angular rates. Rates will be integrated to obtain direction cosines in a fashion similar to that described for shuttle vehicle rotational EOM in section 4.3.8.1.2. The direction cosine matrix will transform from the B coordinate system to the T coordinate system. Target vehicle rotational EOM will be updated 10 times each second. This should be adequate for purposes of crew perception, and is sufficient for interface with translational EOM. The conceptual design for target vehicle rotational EOM is sketched in figure 4.3.8.2.2.-1.

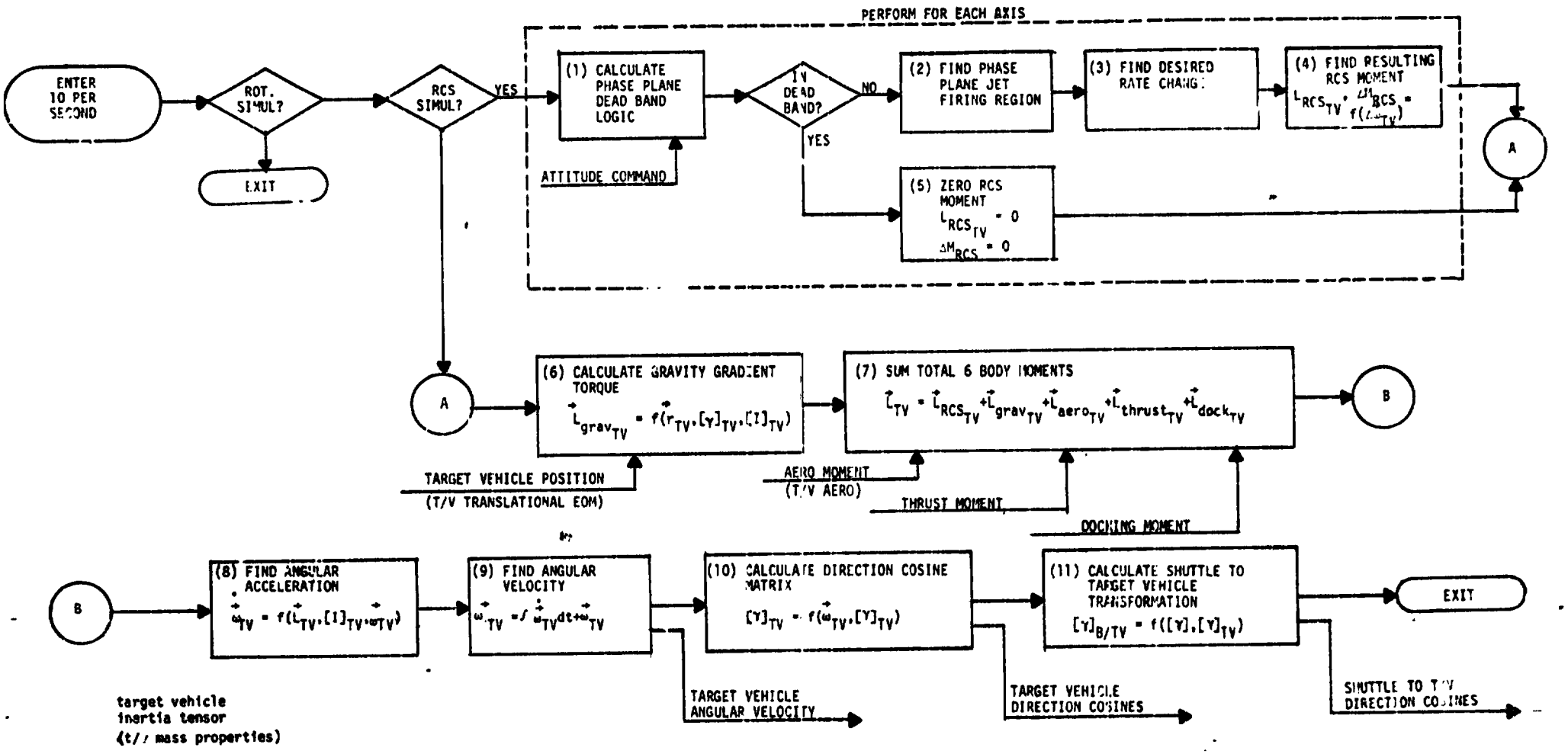


FIGURE 4.3.8.2.2-1 TARGET ROTATIONAL EOM AND ATTITUDE CONTROL

Symbol Dictionary for Figure 4.3.8.2.2-1

$\vec{L}_{aero_{tv}}$	target vehicle aero moment
$\vec{L}_{dock_{tv}}$	target vehicle docking moment
$\vec{L}_{grav_{tv}}$	target vehicle gravity gradient
$\vec{L}_{RCS_{tv}}$	target vehicle RCS moment
$\vec{L}_{thrust_{tv}}$	target vehicle thrust moment
$\vec{L}_{tv}$	target vehicle total moment
$\vec{r}_{tv}$	target vehicle inertial position
$[\gamma]$	direction cosines, shuttle to inertial
$[\gamma]_{B/tv}$	direction cosines, shuttle to target
$[\gamma]_{tv}$	direction cosines, target to inertial
$\vec{W}_{tv}$	target vehicle angular velocity
$\dot{\vec{W}}_{tv}$	target vehicle angular acceleration
ΔM_{RCS}	mass loss due to RCS thrusting
$\Delta\vec{W}_{tv}$	desired target vehicle rate change

4.3.8.2.3 Mass Properties

Many target vehicles will not require a dynamic real-time mass properties simulation. Over the interval of interest, changes in mass properties will be negligible. Other target vehicles, e.g. those with propulsive stages, will demonstrate significant changes in mass properties. Thus, reset booleans will be provided which will allow dynamic mass property simulation to be bypassed for certain target vehicles. Certain other target vehicles (e.g., SRM's external tank) will have their mass properties calculated elsewhere (in the cases of SRM's or external tank, in the appropriate on-board system simulation programs). Thus, in those cases also, the target vehicle mass properties simulation is bypassed. In those cases in which the simulation is not bypassed, inputs to the simulation are engine mass flow and reaction control system mass flow. Total mass is decremented accordingly. Provision will be made to permit interpolation on mass to obtain target vehicle center of mass and tensor of inertia. Obtaining mass center and inertia tensor as functions of mass has been used previously on the CMS booster simulation, and has provided acceptable accuracy. Similar accuracy standards should be acceptable for almost all target vehicle simulation. An interpolation approach will also be relatively easy to update to a different target vehicle. An iteration rate of twice per second is estimated, under fairly conservative rocket assumptions, to require a 1/2 second overburn to erase resulting error on a 7000 $\frac{ft}{sec}$ ΔV burn, which should be quite acceptable in terms of ability of the crew or ground to notice. Mass distribution parameters could probably be iterated even more slowly, if time is critical. The conceptual design is sketched in figure 4.3.8.2.3-1.

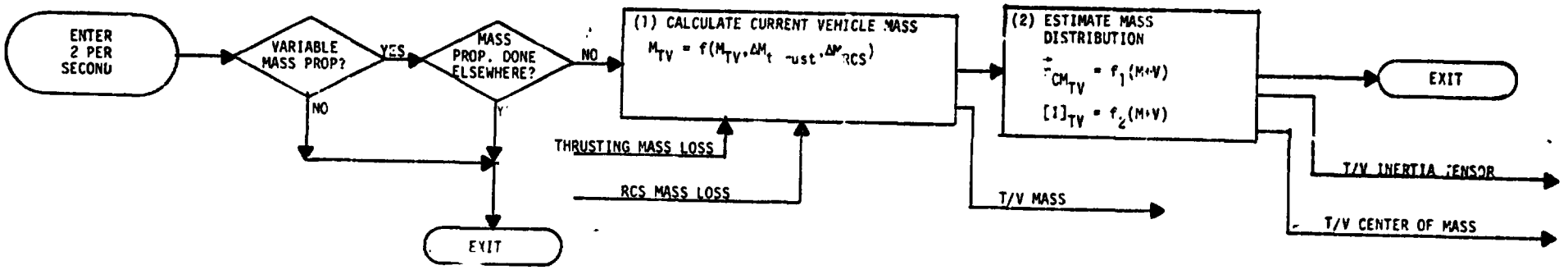


FIGURE 4.3.8.2.3.-1 MASS PROPERTIES

Symbol dictionary for Figure 4.3.8.2.3-1

$[I]_{tv}$	target vehicle inertia tensor	ΔM_{RCS}	mass loss due to target vehicle RCS thrusting
M_{tv}	target vehicle total mass	ΔM_{thrust}	mass loss due to target vehicle engine firing
$\vec{r}_{cm}$	target vehicle mass center location (T/V body axes)		

4.3.8.2.4 Aeroflight Aerodynamics

The simulated target vehicle aeroflight aerodynamics calculates aerodynamic forces and moments on detached target vehicles operating within the atmosphere, (namely boost SRM's and external tank) and proximity atmospheric effects upon both shuttle vehicle and target vehicle. Inputs to simulated aeroflight aerodynamics include target vehicle position, velocity, and attitude (target vehicle translation EØM), target vehicle attitude direction cosines (target vehicle rotational EØM), target vehicle center of mass (target vehicle mass properties) wind and rough air effects (shuttle aerodynamics), shuttle position (shuttle translational EØM), and shuttle attitude direction cosines (shuttle rotational EØM). Velocity of the target vehicle with respect to the moving atmosphere is calculated in the target vehicle body-fixed coordinate system using the same wind and rough air effects which are included in shuttle aerodynamics. Speed of sound and atmospheric density are obtained from the same median profiles used by shuttle aerodynamics as functions of altitude only. Proximity effects will be calculated as functions of mach number and target vehicle displacement for both vehicles. Aerodynamic forces and moments are computed in the target vehicle body fixed coordinate system. Proximity effects will be included with isolated body characteristics by multiplicative and additive factors to obtain total forces and moments. Definition of parameters upon which aerodynamic coefficients will depend and the mode of calculation of moments was generally obtained from existing incomplete data. As additional data appears, parameter dependencies below should be reviewed and revised accordingly. An iteration rate of 10 per second should prove adequate for simulation of proximity effects, and other accuracy requirements are much lower. The conceptual design is sketched in figure 4.3.8.2.4-1.

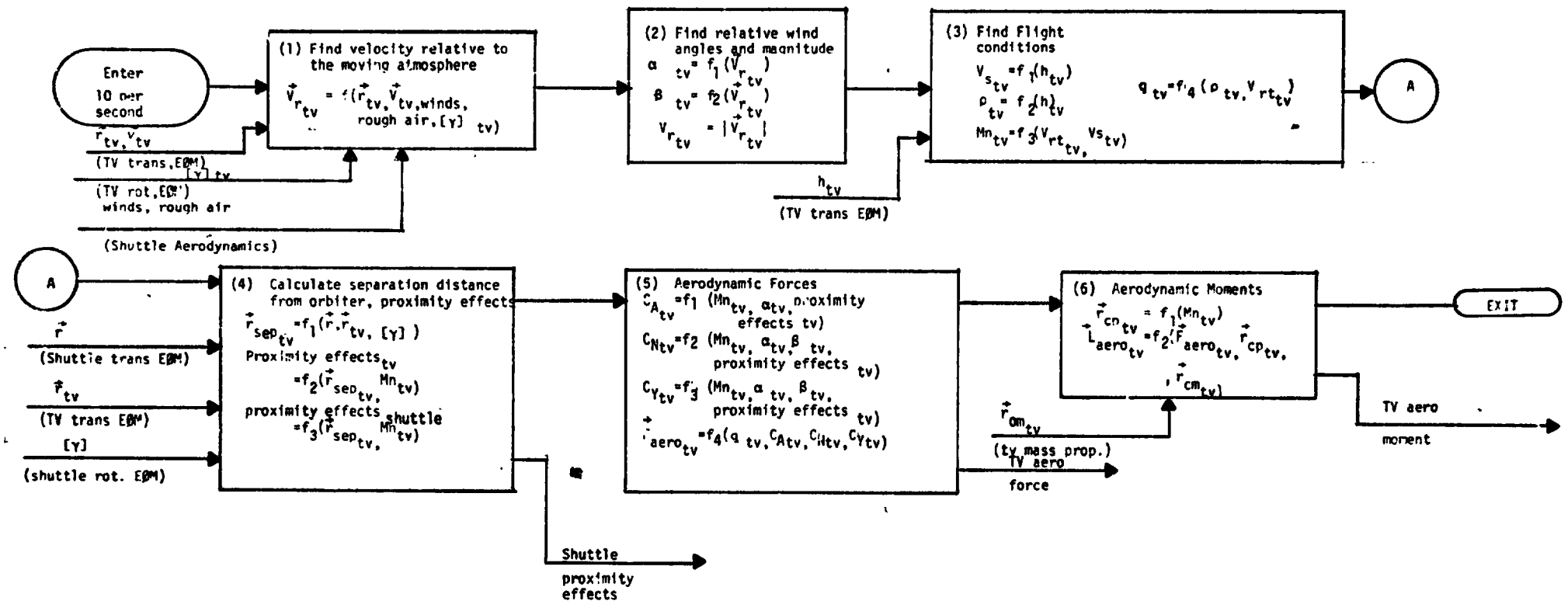


FIGURE 4.3.8.2.4-1 AEROFLIGHT AERODYNAMICS

Symbol Dictionary for Figure 4.3.8.2.4-1

$C_{A_{tv}}$	target vehicle axial force coefficient
$C_{N_{tv}}$	target vehicle normal force coefficient
$C_{\ell_{tv}}$	target vehicle side force coefficient
$\vec{F}_{aero_{tv}}$	target vehicle aerodynamic force
h_{tv}	target vehicle altitude
$\vec{L}_{aero_{tv}}$	target vehicle aerodynamic moment
Mn_{tv}	target vehicle mach number
q_{tv}	target vehicle dynamic pressure
$\vec{r}$	shuttle position
$\vec{r}_{cm_{tv}}$	target vehicle c.m. location
$\vec{r}_{cp_{tv}}$	target vehicle center of pressure position
$\vec{r}_{tv}$	target vehicle position
$\vec{V}_{r_{tv}}$	target vehicle velocity with respect to moving atmosphere
$V_{s_{tv}}$	target vehicle speed of sound
$\vec{V}_{tv}$	target vehicle velocity
α_{tv}	target vehicle angle of attack
β_{tv}	target vehicle sideslip angle
$[\gamma]$	shuttle vehicle direction cosines
$[\gamma]_{tv}$	target vehicle direction cosines
ρ_{tv}	target vehicle atmospheric density

4.3.8.2.5 Spaceflight Aerodynamics

The simulated target vehicle spaceflight aerodynamics calculates aerodynamic forces and moments on detached spaceflight target vehicles (all target vehicles except boost SRM's and external tank). Inputs to simulated spaceflight aerodynamics include target vehicle position, velocity, and altitude (target vehicle translational EØM), and target vehicle attitude direction cosines (target vehicle rotational EØM). Velocity of the target vehicle with respect to the atmosphere is calculated in the target vehicle body-fixed coordinate system, assuming an atmosphere rotating uniformly with the earth. Atmospheric density is obtained from the same median profile used by shuttle aerodynamics as a function of altitude alone. Definition of parameters upon which aerodynamic cooefficients will depend was generally obtained from existing incomplete data. As additional data appears, parameter dependencies below should be reviewed and revised accordingly. An iteration rate of twice per second is chosen to match that of orbital shuttle aero. It can be justified for the reasons given in section 4.3.8.1.4. The conceptual design is sketched in figure 4.3.8.2.5.-1.

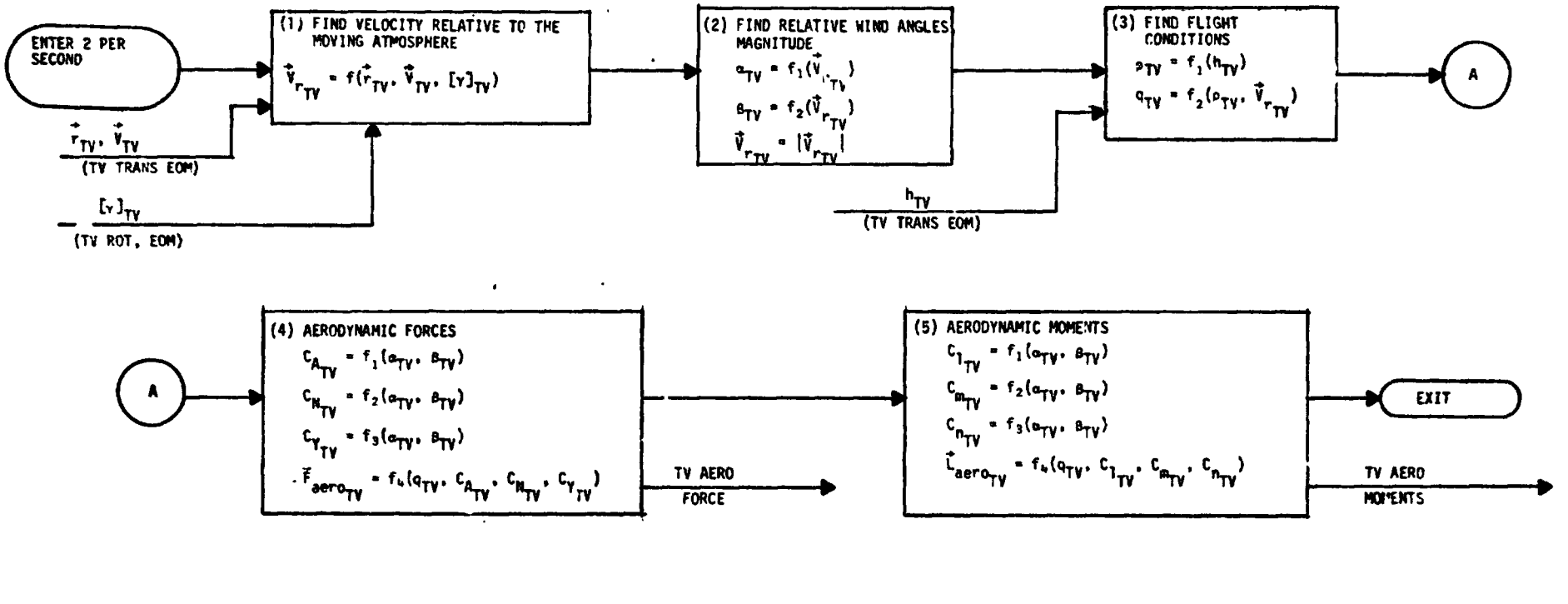


FIG. 4.3.8.2.5.-1 SPACEFLIGHT AERODYNAMICS

Symbol Dictionary for Figure 4.3.8.2.5.-1

$C_{A_{tv}}$	target vehicle axial force coefficient
$C_{\ell_{tv}}$	target vehicle rolling moment coefficient
$C_{m_{tv}}$	target vehicle pitching moment coefficient
$C_{n_{tv}}$	target vehicle yawing moment coefficient
$C_{N_{tv}}$	target vehicle normal force coefficient
$C_{Y_{tv}}$	target vehicle side force coefficient
$\vec{F}_{aero_{tv}}$	target vehicle aerodynamic force
h_{tv}	target vehicle altitude
$\vec{L}_{aero_{tv}}$	target vehicle aerodynamic moment
q_{tv}	target vehicle dynamic pressure
$\vec{r}_{tv}$	target vehicle position
$\vec{V}_{r_{tv}}$	target vehicle velocity with respect to moving atmosphere
$\vec{V}_{tv}$	target vehicle velocity
α_{tv}	target vehicle angle of attack
β_{tv}	target vehicle sideslip angle
$[Y]_{tv}$	target vehicle direction cosines
ρ_{tv}	target vehicle atmospheric density

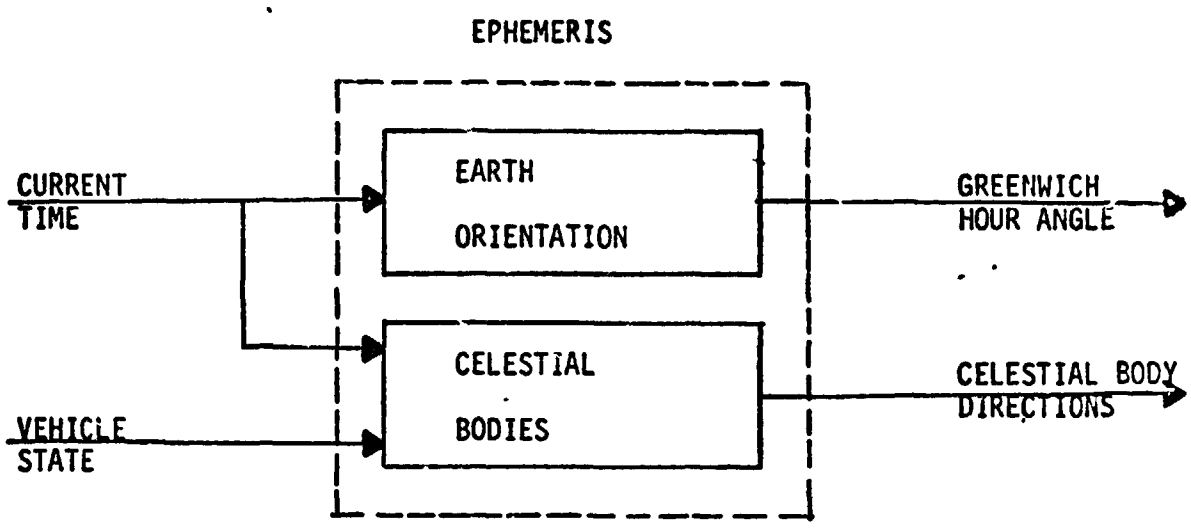
4.3.8.3 Ephemeris

The real-time ephemeris program must perform two functions:

determine earth orientation

determine directions of celestial bodies

at any point in time during the mission. Accordinly, the real-time ephemeris program may be functionally conceived as follows:



4.3.8.3.1 Earth Orientation

The precession and nutation of the earth's equator and the rotation of the earth about its polar axis determine the orientation of the earth in inertial space. Over a period of seven days, reorientation of the equator due to precession and nutation are not significant (less than two arc-seconds in any axis). Thus, it will be assumed that the equinox and spin axis remain inertially fixed over that period. The earth's spin may be described by the True Greenwich Hour Angle, which is the angle from the true vernal equinox to the intersection of the Greenwich Meridian and the Equator. To achieve the required accuracy of $\pm$ 2 arc-seconds, without perceptible jitter, the Hour Angle will be updated ten times per second. The Earth's axial rotation rate

is about 15 $\frac{\text{arc-sec}}{\text{sec}}$. Thus, at this iteration rate, the Hour Angle is always maintained within $\pm$ 1.5 arc-sec., which is equivalent to about 150 feet (ground-track) at the equator. No formal calculation of an earth-fixed to inertial coordinate transformation matrix will be performed. As the T coordinate system is used for the inertial system and the E coordinate system is used for the earth-fixed system, this transformation consists solely of a rotation through the Hour Angle. This can be most efficiently accomplished by an angle rotation rather than a matrix multiplication. Hence, the sine and cosine of the Hour Angle are maintained rather than a transformation matrix. The conceptual design is presented in figure 4.3.8.3-1..

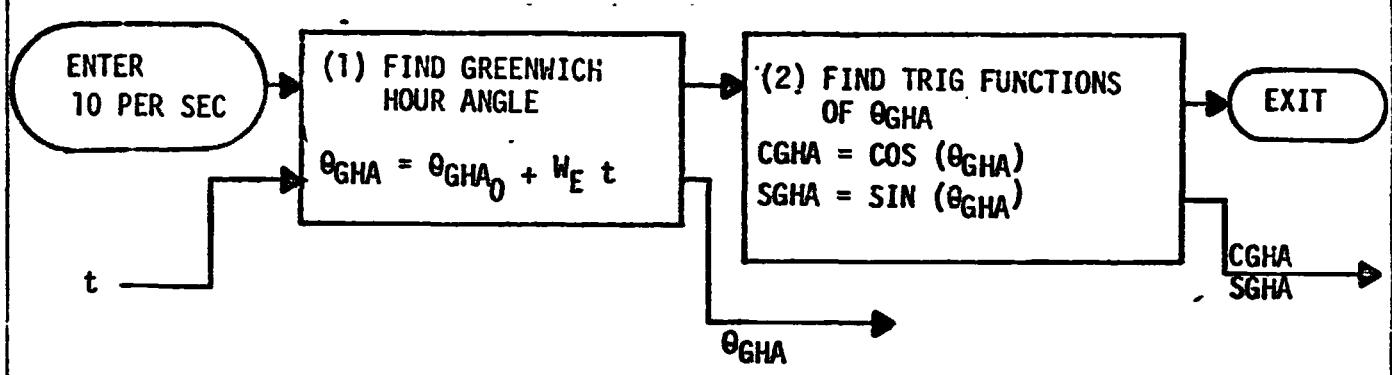


Figure 4.3.8.3-1 EARTH ORIENTATION

Symbol Dictionary for Figure 4.3.8.3-1

CGHA	cosine of θ_{GHA}	θ_{GHA}	True Greenwich Hour Angle
SGHA	sine of θ_{GHA}	θ_{GHA_0}	True Greenwich Hour Angle at liftoff (reset constant)
t	elapsed time since liftoff	W_E	Hour Angle rate (reset constant)

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If it is desirable to save time at the expense of core, numerous time-consuming calculations of the exact trig functions of Θ_{GHA} can be avoided. The exact trig functions can be calculated only once every five seconds, while CGHA and SGHA are updated in the interim using the following approximations:

$$\text{SIN}(\Theta + \Delta\Theta) \approx \text{SIN}\,\Theta + (\Delta\Theta)\,\text{COS}\Theta$$

$$\text{COS}(\Theta + \Delta\Theta) \approx \text{COS}\,\Theta - (\Delta\Theta)\,\text{SIN}\Theta$$

This procedure will not create errors exceeding $2X10^{-9}$ in the trig functions, which is quite acceptable.

4.3.8.3.2 Celestial Bodies

The inertial directions (from the vehicle) of the following celestial bodies will be maintained:

Sun	(also solar occlusion will be calculated)
Moon	
Planets	(Mercury, Venus, Mars, Jupiter, Saturn)
Stars	(detectable by star tracker)

Planetary, lunar and solar directions will take into account both the changing true directions of the other celestial bodies with respect to the earth, and the position of the vehicle with respect to the earth. Relative motion of sun, stars, ecliptic plane and equatorial plane are negligible over the duration of a mission, compared to the tolerances specified in the requirements. They will be ignored. Stellar parrallax is negligible (less than $\pm$ 1 arc-second). Thus, true directions of the stars will be provided in a table of reset constants. Aberration effects can reach 25 arc-seconds for solar, planetary, and stellar observations, so they must be included. Lunar aberration is much less (about 5 arc-sec maximum) and can be ignored. The program will calculate the apparent positions of sun and

planets only. Since apparent position of only a few particular stars must be known at any given time, it is more efficient to perform abberration corrections in the using programs (e.g., star tracker) for just those stars required. The ephmeris will, however, provide certain generalized terms used in the calculation of stellar aberration. True earth-referenced positions and velocities (velocities are required for aberration correction) of sun, moon, and planets will be obtained in real-time by interpolation on pre-stored tables. Jet Propulsion Laboratory (JPL) Ephemeris tapes will serve as the source for the pre-stored tables. JPL tapes contain data up to the year 2000. The reset generator program will scan the JPL tape, and strip and condition appropriate blocks of data for use by the real-time program. Time tags will be changed to reflect mission elapsed time. Interpolation will be done using an Everett's interpolation scheme. All directions will be output in the appropriate T coordinate system. Since JPL data (and probably star data) will be in the S coordinate system, the reset generator will reform the necessary transformation to place it in the T coordinate system. To remain safely within tolerances specified in the requirements, the following minimum iteration rates are desirable:

Moon	once per 5 seconds
Mercury	once per 45 seconds
Venus	once per 75 seconds
Mars	once per 1-3/4 minutes
Jupiter	once per 3-1/2 minutes
Sun	once per 5 minutes
Saturn	once per 7 minutes
Stars	once per 15 minutes

While a slower iteration rate than once per five seconds is feasible for all bodies except the moon, it is questionable whether the amount of time saved would justify the ensuing conceptual complication (or small additional core requirement). Since orbital sunrise requires about eight seconds, such an update rate for solar occlusion should be acceptable. The resulting conceptual design is sketched in figure 4.3.8.3-2.

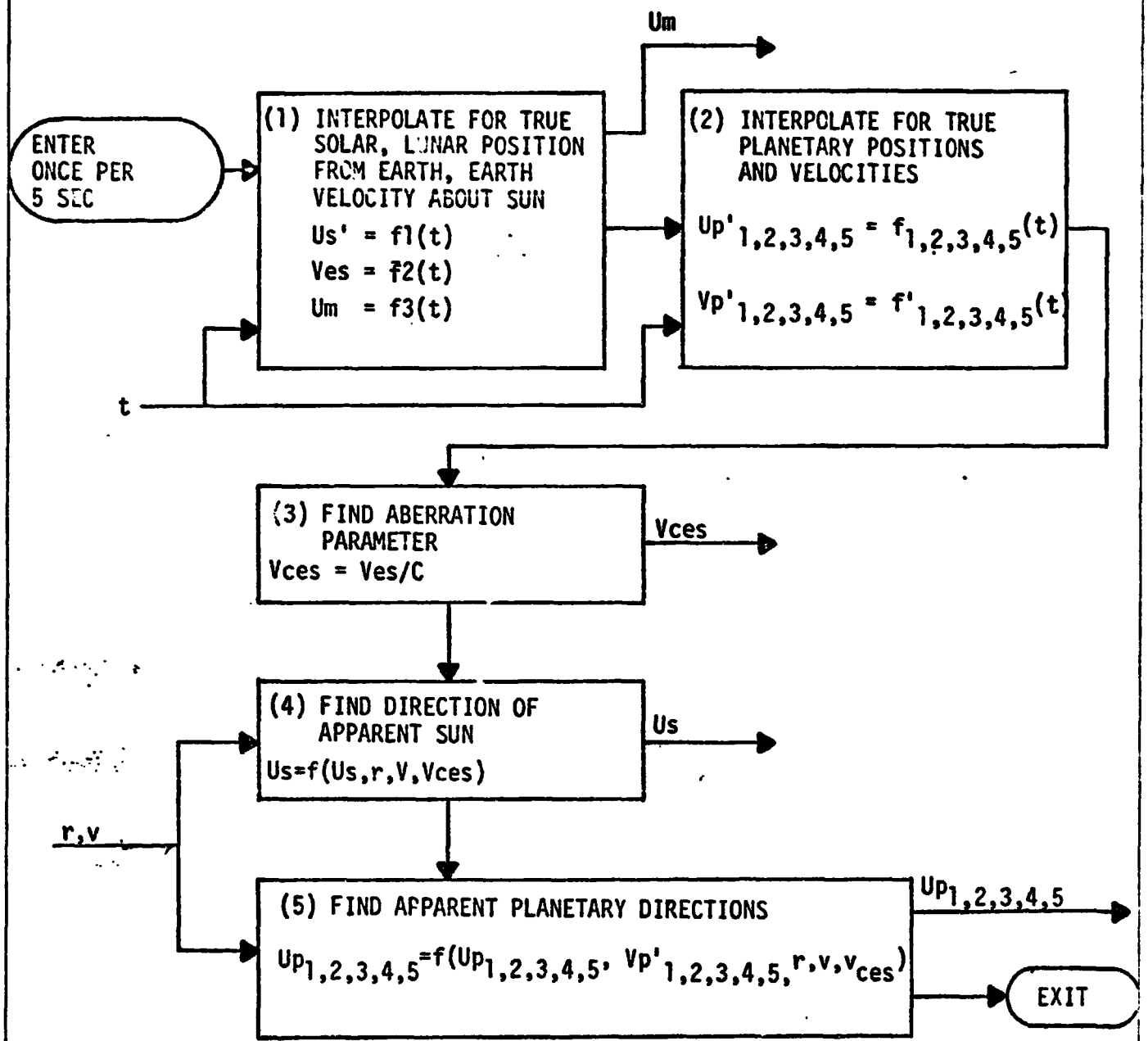


Figure 4.3.8.3-2 CELESTIAL BODIES

Symbol Dictionary for Figure 4.3.8.3-2

C	speed of light (constant)	U_s	unit vector in apparent direction of sun
Nso	boolean indicating solar occultation vehicle position (T system)	U_s	true position of sun
t	elapsed time since liftoff	V	vehicle inertial velocity (T system)
U_m	unit vector in direction of moon	V_{ces}	$\frac{1}{c}(V_{es})$
$U_{p1,2,3,4,5}$	unit vector in apparent direction of planet	V_{es}	velocity of earth about sun
$U_{p1,2,3,4,5}$	true position of planet	$V_{p1,2,3,4,5}$	velocity of planet

4.3.9 Thermal System

The Thermal System is divided into three major subsystems: Thermal Protection (TPS), Thermal Control (TCS) and Environmental an Life Support (ECLSS).

Throughout the Thermal System Simulation, the laws of conservation of mass and energy will be applied. For example, heat exchangers and coldplates will transfer heat to the coolant medium (water, freon, etc.) according to:

$$\Delta T_1 = \frac{\dot{Q}_{1N}}{\dot{W}_1 C_{P1}}$$

where: ΔT_1 = outlet temperature minus inlet temperature

$\dot{Q}_{in}$ = heat transfer rate into coolant

$\dot{W}_1$ = flow rate of the coolant

C_{P1} = specific heat of the coolant

Then the temperature change across heat generating (absorbing) components can be given as:

$$T_{out} = T_{in} + (\Delta T_1)(K)$$

where: T_{out} = coolant outlet temperature

T_{in} = coolant inlet temperature

K = iteration rate (executions/unit time)

The calculations for the heat transfer rate, $\dot{Q}in$, will account for coolant properties, physical dimensions and flow characteristics:

$$\dot{Q}_{in} = f(D_1, \dot{W}_1, C_{P1}, K_1, \Delta T_2, \Delta X_1, K_2, A_1)$$

where: D_1 = effective diameter of coolant passage

K_1 = thermal conductivity of coolant

ΔT_2 = temperature difference, coolant to component.

ΔX_1 = effective conduction thickness

K_2 = thermal conductivity of component material

A_1 = area of heat flux

Radiation heat transfer calculations will be derived from the general equation:

$$\dot{Q}_{em} = f(\varepsilon, \sigma, T_1^4)$$

where $\dot{Q}_{em}$ = heat transfer rate due to radiation

ε = emissivity of the radiative surface

γ = Stefan-Boltzmann constant

T_1 = surface temperature

This basic equation will be modified for specific applications to consider surface areas and geometric configuration. For exterior vehicle calculations, solar radiation and radiation emitted and reflected from the earth will be included as well as shadowing effects where they apply.

The net result of heat fluxes into and out of a given volume of any material, solid, liquid or gas will be calculated by the equation:

$$\dot{Q} = f[\Sigma(\dot{Q}_{RAD} + \dot{Q}_{COND} + \dot{Q}_{CONV})]$$

where: $\dot{Q}$ = net heat transfer rate

$\dot{Q}_{RAL}$ = heat transfer due to radiation

$\dot{Q}_{COND}$ = heat transfer rate due to conduction

$\dot{Q}_{CONV}$ = heat transfer rate due to convection

The net heat transfer rate is then integrated against the total

heat content:

$$Q = Q_{n-1} + (\dot{Q})(K)$$

where: Q = total heat content

Q_{n-1} = initial total heat content

And then a new temperature is computed from:

$$T_2 = \frac{Q}{M_1 \, CP_2}$$

where: T_2 = bulk temperature of material

M_1 = mass of the material

C_{p2} = specific heat of the material

Flow rates of compressible fluids will be computed based on differential pressure relationships. In general, the form is:

$$\dot{W}_2 = f(\Delta P_1, D_2)$$

where: $\dot{W}_2$ = the calculated mass flow rate

ΔP_1 = the pressure differential existing across opening or orifice.

D_2 = effective diameter of the opening or orifice.

In each case, conservation of mass will apply to account for the flow rate. For example, the volume which receives flow rate W_2 will have its mass increased by:

$$M_2 = M_{2\ n-1} + (\dot{W}_2)(K)$$

where: M_2 = mass of gas within the volume

$M_{2_{n-1}}$ = initial mass of gas

From this mass calculation, a new pressure may be calculated for use in the next pressure differential calculation:

$$P_1 = f\ (V_1, M_2, R_1, T_2)$$

where: P_1 = pressure of gas

V_1 = volume containing M_2

R_1 = gas constant for the particular gas

T_2 = bulk temperature of the gas

The ideal gas law, PV = MRT, can be used for all compressible gas calculations except at very high pressures and for cryogenic. Empirical equations of state will be used in these cases.

4.3.9.1 Thermal Protection Subsystem

The Thermal Protection Subsystem (TPS) is intended to thermally shield the vehicle from high temperatures during atmospheric flight. Two basic arrangements are planned, one for high temperatures (up to 2500°F) on the leading and lower surfaces of the exterior and one for moderate temperatures (below 650° F) for the upper surfaces.

The simulation will cover both atmospheric and orbital flight cases. A critical altitude will be used to determine which case is dominant, i.e., aerodynamic heating from atmospheric flight or radiative effects encountered in orbital flight.

For the simulation, the exterior vehicle surface will be divided into a number of sections so that heat fluxes and temperatures at various points can be calculated.

4.3.9.1.1 Radiation

Radiation from the following sources will be accounted for in the simulation:

1. Solar
2. Earth emission
3. Solar, reflected from earth
4. Deep space

A constant solar heat flux will be used since the orbital distances are small compared to the distance from earth to the sun. For a given section of area, orientation relative to the sun-earth line will be used to determine the effective area. Figure 4.3.9.1.1.1 shows a typical planar area segment or panel,

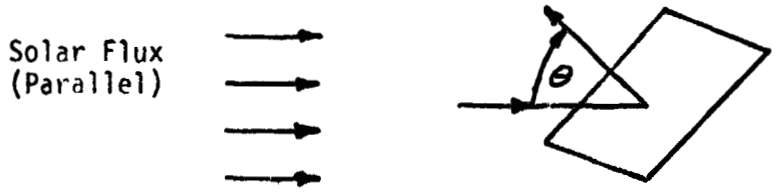


Figure 4.3.9.1.1.1

If the actual surface area is A_2, then correcting for the effective area w.r.t. solar flux, the solar radiation impingement is given by: $\dot{Q}_{sr} = f(A_1, \theta, C_1, \alpha_1)$

or specifically:

$$\dot{Q}_{sr} = (\alpha_1)(C_1)(A_2)(\text{Cos}\theta)$$

where: Q_{sr} = heat transfer to panel due to solar radiation

C_1 = constant for solar heat flux

A_2 = actual area of panel

α_1 = absorptivity of panel surface.

The effects due to the earth's reflection of solar radiation will also employ a constant, determined experimentally, with corrections made for vehicle position relative to the earth-sun line and for orientation relative to the earth-vehicle line. Figure 4.3.9.1.1.2 shows an example.

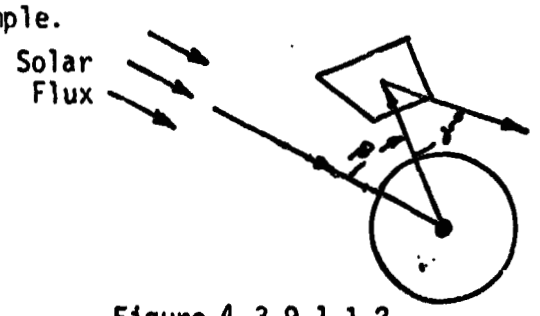


Figure 4.3.9.1.1.2

Again using a planar area segment, the reflected flux will be calculated by: $F_{ref} = f(C_2, \beta)$

or,

$$F_{ref} = (C_2)(\text{Cos } \beta)$$

where: F_{ref} = flux reflected at β

C_2 = constant reflected flux at $\beta = 0$

β = angle between the sun-earth line and the earth-vehicle line

Of this reflected flux, only a portion will strike the panel. If the panel is oriented away from the earth-vehicle line by an angle γ, then the heat transferred to the panel will be:

$$Q_{er} = (F_{ref})(A_3)(\text{Cos } \gamma)$$

where: Q_{er} = heat transfer to panel due to reflected solar radiation

A_3 = actual area of the panel

Both direct and reflected solar radiation will be ignored when the vehicle is in the umbra.

Emission from the earth however will be experienced in and out of the umbra and will be simulated as a constant flux corrected for orientation to the earth-vehicle line.

Another significant heat flux is that radiated away from the exterior surfaces to deep space. In general, the solution will be of the form given in 3.3.9 in the general discussion.

The total heat transfer to a typical elemental section of surface then can be determined by summing all of the above separate components.

$$\dot{Q}_{rad} = \dot{Q}_{sr} + \dot{Q}_{er} + \dot{Q}_{ee} - \dot{Q}_{em}$$

where: $\dot{Q}_{ee}$ = heat transfer due to earth emission

Parameters defining vehicle position and orientation will be utilized to permit dynamic computations for radiation.

4.3.9.1.2 Aerodynamic Effects

Below a critical altitude, the radiation heat transfer is negligible compared to aerodynamic effects. In the simulation, only one or the other will be computed at a given time. Based on test data, an empirical relationship can be developed to determine heat transfer due to aerodynamic heating. The relationship will be based on vehicle velocity, and atmospheric density.

$$\dot{Q}a = f\ (q,\ v,\ \alpha_2,\ A_3)$$

where: Qa = heat transfer due to aero

q = dynamic pressure

v = velocity

α_2 = angle of attack

A_3 = surface area of section

Actual test data will be used to generate curve fit equations. Again, the outer surface will be divided into sections, with a different equation applicable to each.

Figure 4.3.9.1.2 shows a group of sections schematically and provides a simplified picture of the method to be used to calculate the temperature of a given section.

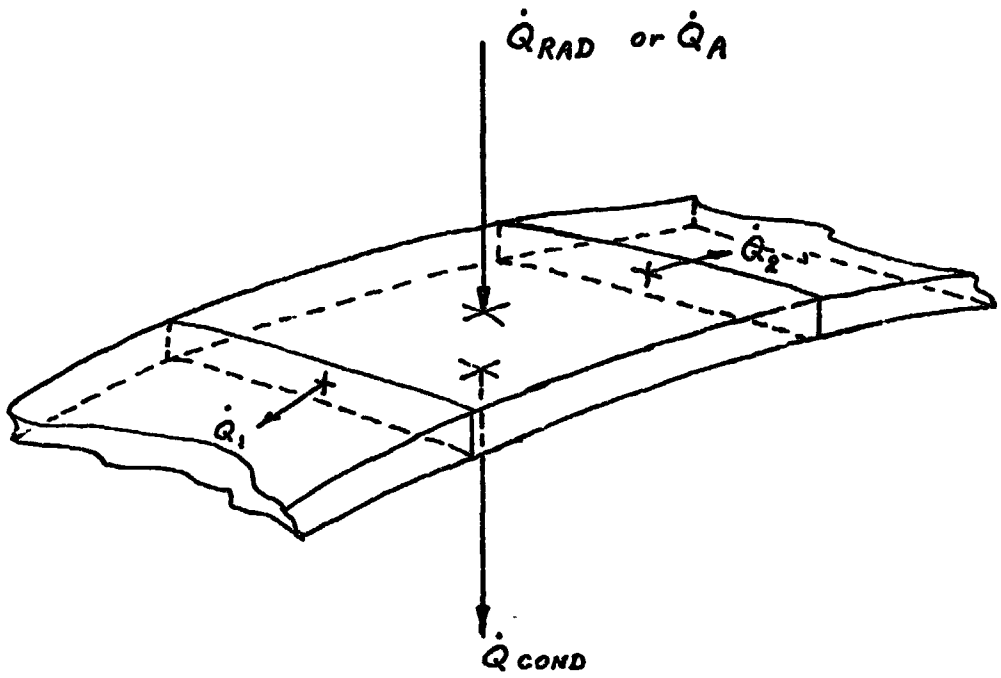


FIGURE 4.3.9.1.2

In this example it can be seen that in addition to the heat transfer already discussed, conduction to neighboring sections, $\dot{Q}1$ and $\dot{Q}2$ will be simulated. All heat transferred into and out of a given section will be summed and its influence on the temperature of the section will be calculated as shown in the general discussion. The TPS equations will be calcualted once per second.

4.3.9.2 Thermal Control Subsystem

This subsystem (TCS) consists mainly of passive elements such as heat sinks, surface coatings and insulators. The subsystem simulation will consist mainly of conduction heat transfer equations. The basic equation is given by:

$$\dot{Q}_{COND} = (K_3)(A_4)(\frac{\Delta T_3}{\Delta X_2})$$

where: K_3 = thermal conductivity of material

A_4 = area normal to heat flux

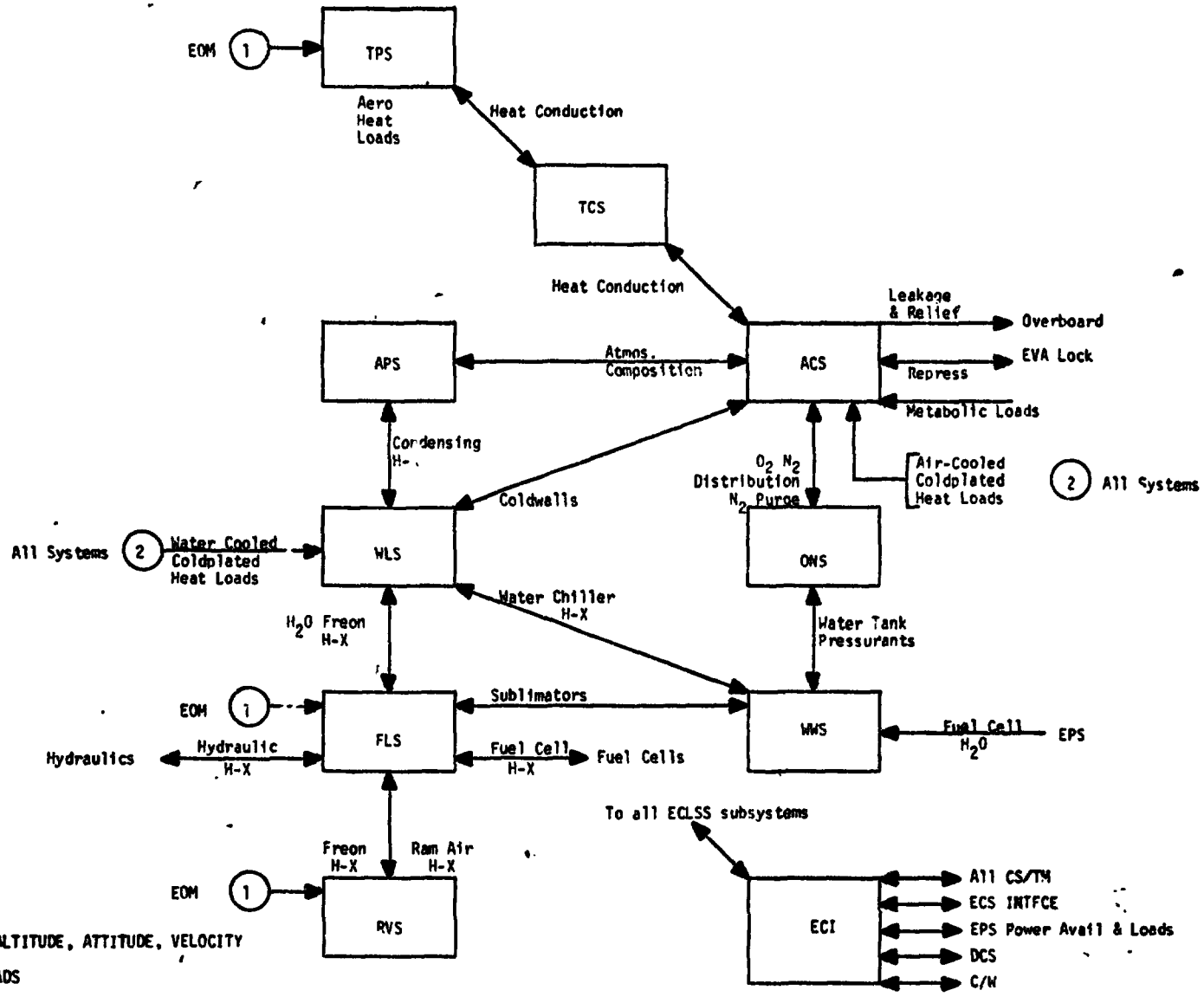
ΔT_3 = temperature differential of two neighboring sections

ΔX_2 = distance between the effective centers of neighboring sections.

The conduction equations will be applied to each layer of insulation material until the cabin walls are reached. At this point, the Environmental Control and Life Support Subsystems will accept the heat flux and determine the influence on the internal walls and cabin atmosphere temperatures. The TCS equations will be executed at a 1/second rate.

4.3.9.3 Environmental Control and Life Support Subsystem

The Environmental Control and Life Support System (ECLSS) simulation will be divided into eight subsystems. Figure 4.3.9.3 shows the principal organization of the subsystems and the basic interface areas. In each case, a written description adjacent to a block indicates that a common item will be simulated in that block. The TPS and TCS are also shown in the figure.



1 EOM PARAMETERS - ALTITUDE, ATTITUDE, VELOCITY

2 EQUIPMENT HEAT LOADS

The ECLSS subsystems will receive crew station switch and digital control commands via the ECLSS interface program (ECI). An iteration rate of 5/second permits momentary switches and digital commands to be read at a satisfactory speed. The program also generates output parameters for crew station meters and lights, telemetry, bus loads and caution and warning. Portions of the program will be executed at a slower rate, 1/second.

The other ECLSS subsystems will contain the equations necessary to accurately simulate the real-world components and equipment. Each subsystem will interface with non-ECLSS subsystems as shown in Figure 4.3.9.3.

The atmosphere circulation subsystem (ACS) will consist of calculations for the cabin, payload compartment, airlock and avionics bay atmospheres. Temperatures, pressures and partial pressures of specific gases will be accounted for. Internal wall heat loads, metabolic heat loads, and air cooled coldplated equipment heat loads will be calculated. Fire detection and provisions for a high nitrogen purge of the avionics bay will be calculated. Calculations for EVA lock pressurization as well as nominal cabin gas leakage and overboard relief valves will be included. An iteration rate of 5/second will be used in order to stabilize the flow rate as a function of the differential pressure between compartments.

The atmosphere purification subsystem (APS) contains the simulation for the condensing heat exchangers, carbon dioxide removal and cabin fans. This subsystem will interface with ACS regarding the composition of the cabin atmosphere. The heat transfer in the condensing heat exchangers will be calculated in this program. A 2/second iteration rate will be used.

The water loop subsystem (WLS) will contain the equations for pumps, loop flow rates and pressures, cabin coldwalls (whose convective effects will be simulated in the ACS), water cooled coldplated equipment, the avionics bay heat exchanger, the water/freon heat exchanger and the water chiller heat exchanger. Iterations at 1/second will be used.

The freon loop subsystem (FLS) will provide for the simulation of pumps, loop flow rates and pressures, the fuel cell heat-exchanger, the hydraulic heat exchanger, the radiators, the sublimators and the payload heat exchanger. The GSE heat exchanger does not require simulation. The discussion given in 4.3.9.1.1 describing radiation calculations will also apply to the radiators in the FLS. The FLS will perform the heat transfer calculations for the fuel cell and hydraulics programs. Altitude, attitude and velocity will be used to determine radiator performance. The program will be calculated at a 1/second rate.

The oxygen/nitrogen subsystem (ONS) will be simulated in detail. All supply tanks, manifolds, valves, regulators and two gas controls will be included. This subsystem provides either oxygen or nitrogen to ACS as required by the two gas controller logic. Nitrogen pressurant is also provided to the waste/water subsystem water tanks. All calculations for the water tank pressures as a function of nitrogen pressurant will be performed in the ONS. A calculation rate of 2/second will be used.

The waste/water subsystem (WWS) will compute the accumulation and disposal of waste and potable water. The masses and temperatures in each tank will be computed in this program. Excess water from the fuel cells will be added to the potable H_2O tank. Water from this tank will be sent to the FLS where the sublimator equations are located. The waste tank will accumulate condensate from the APS condensing heat exchanger calculations. A 1/second iteration rate is adequate for the WWS simulation.

The ram vapor subsystem (RVS) will contain all calculations required for the vapor cycle coolant loop. Included in this loop are the ram air heat exchanger, the freon heat exchanger, compressor and expansion valve. Altitude, attitude, and velocity will be primary inputs for the ram air heat exchanger calculations. These calculations will be ignored at extremely high altitudes where the air density is negligible. This program will be executed at a 2/second rate.

4.3.10 Payload Accommodation System

The simulator payload accommodation system will simulate the operation of the payload manipulator arms, payload attachment devices, payload bay doors, and the payload bay lighting and television subsystems. The simulated payload accommodation system will receive inputs from the simulated equations of motion (shuttle and target vehicle state, target vehicle mass properties), the electrical power subsystem (power availability), the hydraulic power subsystem (power availability), the crew station, and the instructor station (malfunctions, biases, etc.). Information will be provided on payload attachment status, arm dynamics, payload door position; light, camera, and monitor operation; electrical power loadings, and hydraulic flow. The basic configuration and data interchnage of the simulated payload accommodation system is illustrated in Figure 4.3.10.

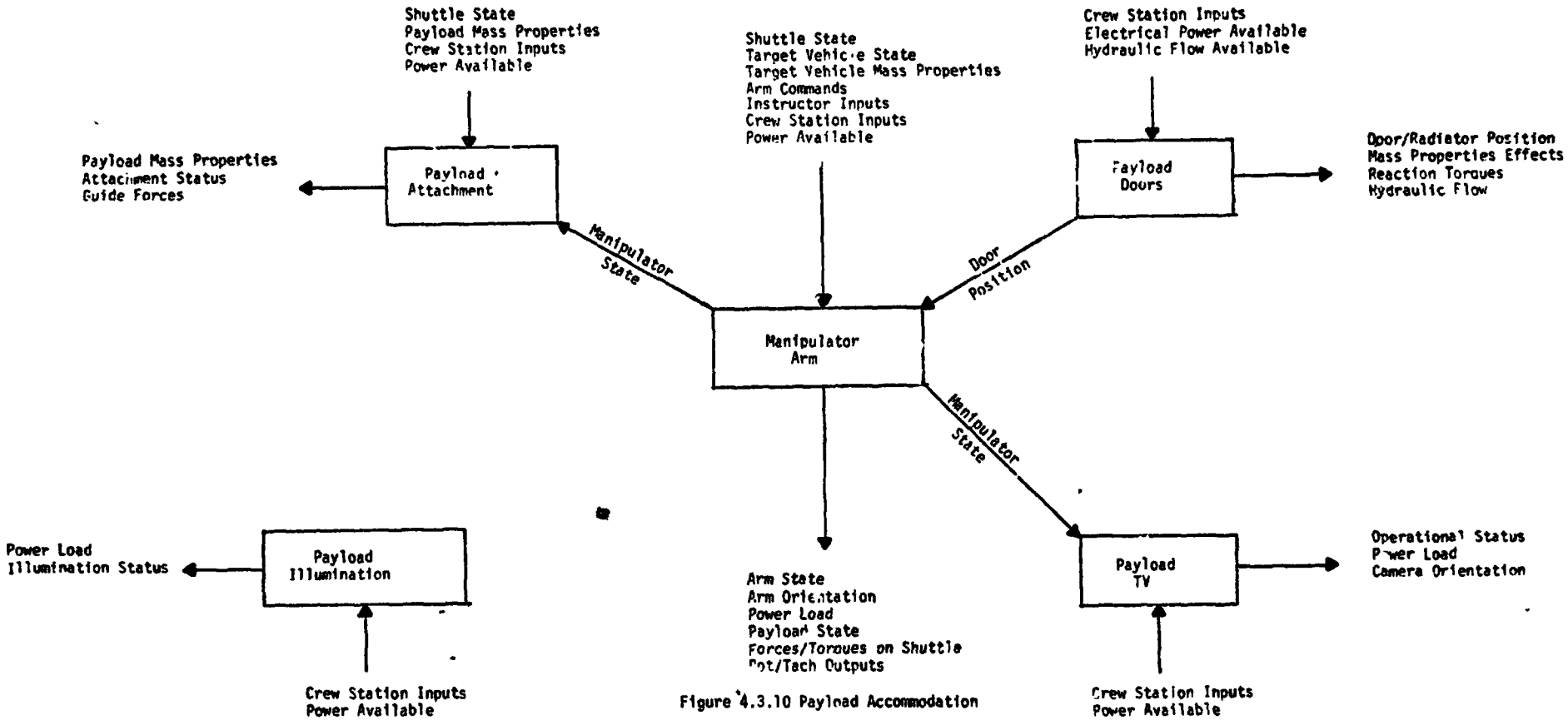


Figure 4.3.10 Payload Accommodation

4.3.10.1 Payload Attachment Subsystem

The simulated payload attachment subsystem simulates the operation and effects of the real-world subsystem of the same name. The simulated payload attachment is iterated once for each applicable payload. If the payload is detached, forces (if any) exerted upon the payload by the attachment fitting payload trunnion guides will be calculated for proper dynamics simulation. Account will be taken of payload motion as well as payload position in calculation of such forces, to ameliorate effects of sampling lag. Attach commands will be honored only if switch and breaker settings are proper and power is available. A payload will be attached when the command is issued, and position and velocity of payload attachment points with respect to shuttle retention points is within the applicable constraints. When a payload has just been attached, its mass center position and inertia tensor with respect to shuttle body coordinates will be calculated for use in the calculation of mass properties. An attached payload will be checked for a release command. A release command will exist when switch and breaker settings are proper and power is available. At the point at which a payload is released, its state for target vehicle EOM will be initialized using shuttle state and retention state with respect to the shuttle vehicle. Its mass properties also will cease to be included into shuttle vehicle mass properties. It will be assumed that a payload, once attached, remains fixed with respect to the shuttle. Preliminary data implies that, in the real-world, this will be the case to within 0.5°. At this point, it would appear that any effects on vehicle inertia tensor resulting from such motion will be sufficiently small as to not require simulation for training purposes. Center of mass shifts permitted are not known, but are also assumed to be insignificant. Precise simulation of continuum effects of such mass property shifts would probably be ruled out in any case due to cost vs. benefit. Rough approximation of retained payload dynamics and resulting momentum effects would be somewhat less costly, but still does not appear to be justified by currently available data. The payload attachment

simulation will be calculated for each applicable payload once each 100 milliseconds. This rate matches that of the manipulator dynamics and the applicable shuttle mass properties, and is sufficiently fine to avoid noticeable delays in mass property changes and payload release.

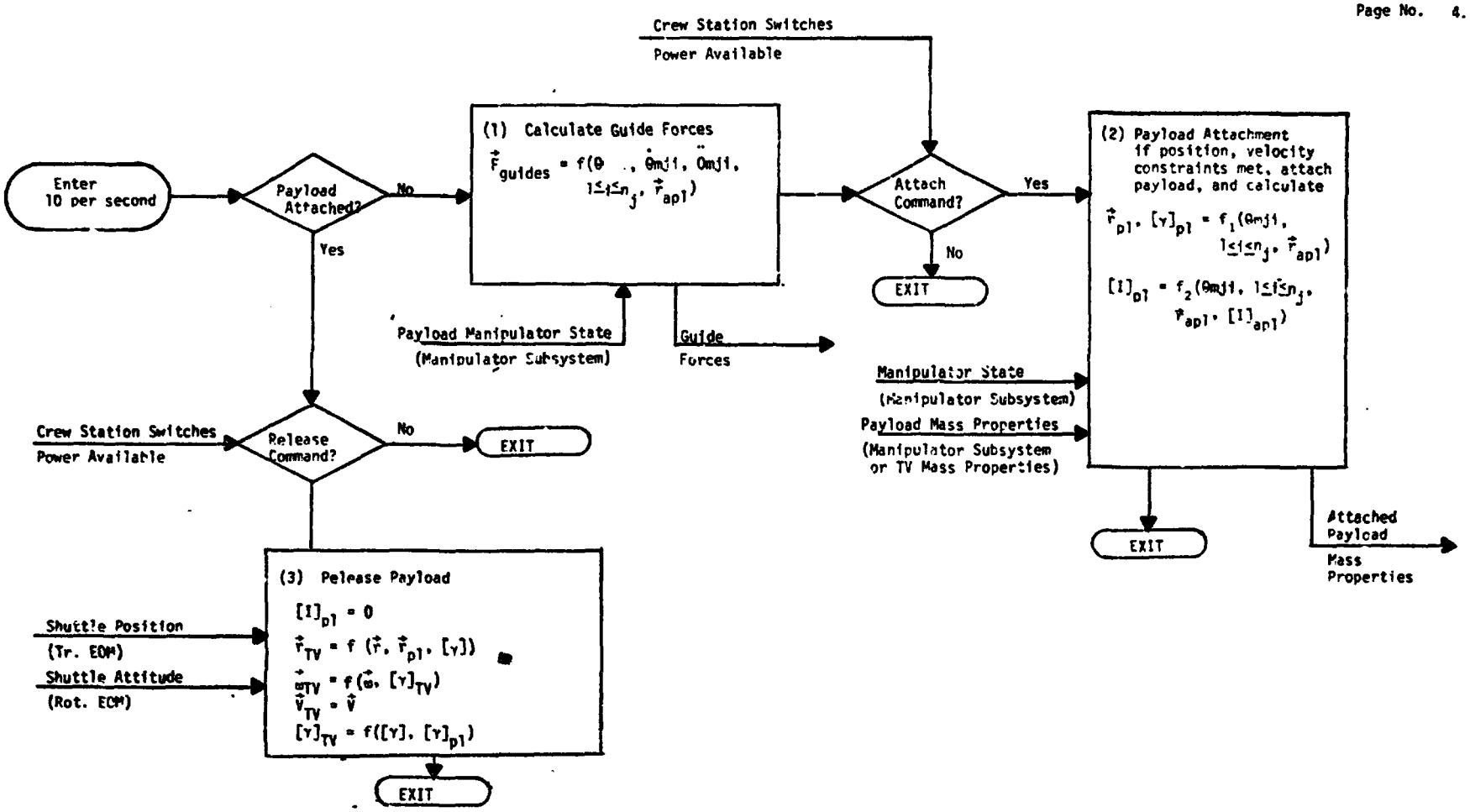


FIGURE 4.3.10.1-1

Symbol Dictionary for Figure 4.3.10.1-1

$\vec{F}_{guides}$	Forces exerted by attachment guides upon payload	$\vec{r}_{tv}$	Target vehicle position
$[F]_{apl}$	Inertia tensor of manipulated payload	$\vec{V}_{tv}$	Target vehicle velocity
$[I]_{pi}$	Inertia tensor of retained payload	$[\gamma]$	Shuttle direction cosines
n_j	Number of arm degrees of freedom	$[\gamma]_{pl}$	Payload attached attitude
$\vec{r}$	Shuttle position	$[\gamma]_{tv}$	Target vehicle direction cosines
$\vec{r}_{apl}$	Position of manipulated payload	θ_{mji}	Position of e^{th} manipulator joint angle
$\vec{r}_{pl}$	Retained payload center of mass position	$\dot{\theta}_{mji}$	Rate of e^{th} manipulator joint angle
		$\ddot{\theta}_{mji}$	Acceleration of e^{th} manipulator joint angle
		$\vec{\omega}$	Shuttle angular velocity
		$\vec{\omega}_{tv}$	Target vehicle angular velocity

4.3.10.2 Payload Manipulator Subsystem

The simulated payload manipulator subsystem simulates the dynamics and interfaces of the shuttle payload manipulators. Inputs to the simulated subsystem include manipulator arm joint and terminal device position commands (from the on-board computers), power available booleans (from the electrical power subsystem) shuttle vehicle translational state and body forces (from translational EOM), shuttle vehicle attitude, angular velocity and total moments (from rotational EOM), payload position (from target vehicle translational EOM or the payload accommodation system), payload attitude (from target vehicle rotational EOM or the payload accommodation), payload mass inertia tensor and c.m. location (from payload mass properties), and crew station switch and circuit breaker settings. Provided these inputs, the manipulator simulation will calculate each manipulator joint angle position and rate, terminal device and deployment device positions, joint potentiometer and tachometer outputs, forces and torques exerted upon the vehicle by the manipulator system, payload translational and rotational state upon release, electrical power loads, checkout system outputs, and relative state of a jettisoned arm. Definition of the vehicle payload manipulator subsystem is quite amorphous and indefinite at this time. The real-world configuration herein simulated is based on what is apparently the best available data, but should not be regarded as a high-confidence delineation of the ultimate real-world system. It is entirely possible that, as real-world system design progresses, substantial changes will be required in this conceptual design. The vehicle possesses two manipulator arms, each of which will be simulated as discussed below. If all proper crew station switches and breakers are set and power is available and the arm jettison switch is thrown, the arm will be jettisoned. The relative state of the jettisoned arm will be maintained until it has safely cleared the vehicle, for simulation of visual cues to verify separation, enhanced visual realism, and collision avoidance training. The jettisoned arm will be assumed to be given a fixed impulse, from which its relative velocity will be calculated once,

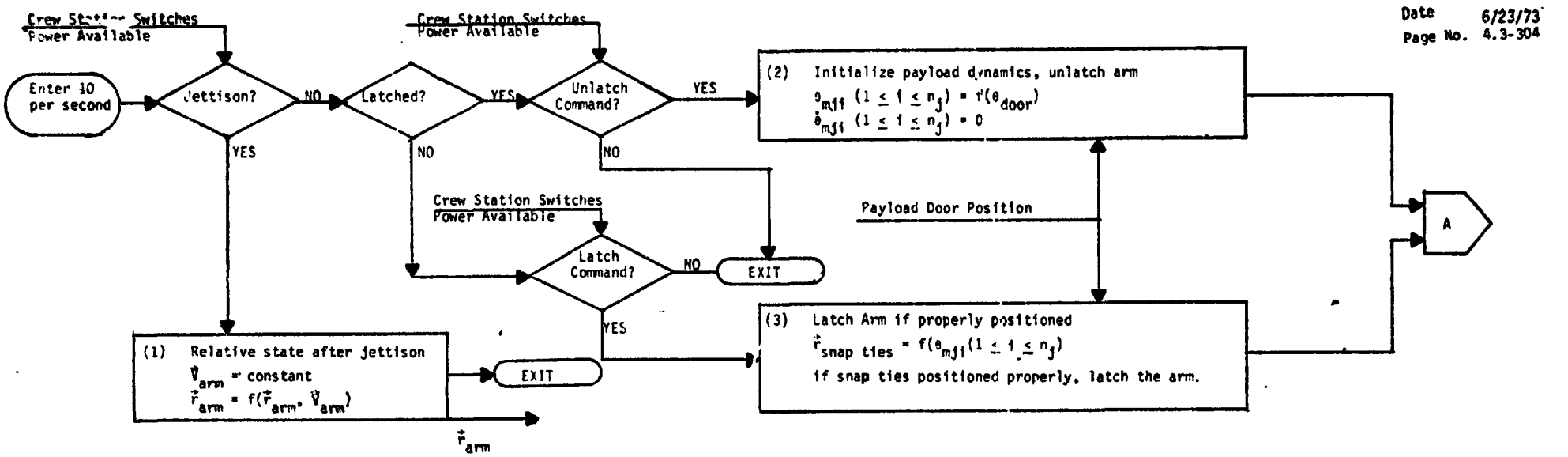
and held constant thereafter. There does not seem to be a great amount of training value in maintaining relative rotational state of the jettisoned arm or inertial state of the jettisoned arm (though they would improve realism). The jettison forces and torques on the shuttle will be simulated. The attachment of the manipulators to the payload doors will be simulated. When the arm is latched, the proper switch and breaker configuration exists, power is available, and the unlatch switch is thrown, the simulated arm will be released, and the arm dynamics simulation initialized with the "stowed" joint angles, and zero angular rates. When the arm is unlatched, the proper switch and breaker configuration exists, power is available, and the unlatch switch is thrown, the orientation of the arm will be checked. If the arm snap ties are properly positioned, the simulated arm will be latched. If, however, the function of the real-world latch switch is to command an arm trajectory to the latching position, after which time an automatic latch command is given, the latches will be actuated by that automatic command. During periods during which the arm is latched, arm dynamics will not be calculated. If latching or unlatching can take place at variable door positions, the initial joint angles upon unlatching will be set, and the proper snap tie positions upon latching will be determined, as appropriate, as functions of payload door position. The arm deployment mechanism will be simulated as active whenever the proper switch and breaker configuration exists, power is available, a switch commanding change in deployment state is thrown, and redeployment is not complete. While active, the mechanism will be considered to move at a constant rate until the appropriate limiting position is attained. Deployment device position, position of the manipulator arm shoulder with respect to the body axis system and power load will be calculated. The terminal device simulated will be a simple grasping device. The terminal device simulation will, however, be kept functionally and physically separate from the remainder of the arm simulation as much as possible. Thus, update by modification to an alternate terminal device

will be simplified, if it is required. It is assumed that the device will grasp the payload rigidly, and will have only one degree of freedom, namely the joint between the grasping bars. The simulated terminal device will be active when power is available and the proper crew station switch and breaker configuration exists. It is assumed that the terminal device can receive drive signals from either the on-board computers or the manual checkout system. On-board computer signals will be assumed to be the joint position command, while checkout system signals will be assumed to be direct motor torque command, which is at any given time either zero or $\pm$ a fixed number. The terminal device simulation will include servo-loop dynamics if significant in computing motor torques. Terminal device mass properties (which are constant) will be used in conjunction with torque to obtain angular acceleration, angular rate, and angular position of the terminal device joint. Outputs to the checkout system readouts and power load will also be calculated. If the terminal device was just closed (i.e., joint angle reduced below a certain point), the terminal device position is compared to the positions of grasping points of all payloads in the area (obtained from the payload accommodation system or target vehicle EOM as appropriate). If these comparisons indicate that a payload was grasped, its mass and inertia properties will be stored in the appropriate cells and its orientation with respect to the arm's wrist joint will be calculated for use in the arm dynamics simulation. If the terminal device was just opened (i.e., joint angle increased above a certain point), and a payload had been grasped, and that payload is not now attached to the shuttle vehicle by the payload attachment subsystem, the target vehicle Equations of Motion for that payload are initialized. Payload position, velocity, attitude, and angular rates at release are calculated using current shuttle vehicle translational and rotational state, as well as arm joint angles and angular rates. At release, the mass and inertia of the grasped payload will be reset to the unloaded condition in the arm dynamics simulation. Providing that power is available and crew station switch

settings are properly configured, the manipulator arm torque motors will be considered active. During times at which the arm is not stowed, when a given joint does not have power available, it is assumed that brakes will be applied to that joint. It is assumed that each joint can receive drive signals from either the on-board computers (in the form of joint position commands) or the manual checkout system (in the form of direct motor torque commands, which are, at any given time, either zero or $\pm$ a fixed number). Servo-loop dynamics will be included in the calculation of torque resulting from drive signals if significant. Torques will be limited to the same values that real-world arm torques are limited. Joint torques will reflect the effects of the malfunction of one of the motors on that joint when appropriate. Checkout system outputs, power load, and torques on each joint are calculated from the input information. Arm dynamics will be simulated by solving the rigid-body equations of motion for the shuttle/manipulator/payload system. Bending frequencies are currently constrained to an amplitude substantially less than the control system tolerance, which is presumably smaller than the minimum accuracy envelope required to perform all required tasks. Thus, the simulation of arm bending effects does not at this time appear to provide sufficient training value to offset the very considerable impact resulting from its inclusion. The data on which this conclusion rests may be invalidated as the arm design develops. Based upon data available at this time, it is estimated that if bending mode simulation is required, the computer requirements in addition to the basic simulation are 1,000 data words, 3,000 executable instructions, and 300,000 instructions per second. When unloaded, the manipulator will be assumed to consist of three segments (shoulder to elbow, elbow to wrist, wrist through terminal device), each with significant mass. When loaded, the mass, inertia properties and center of mass location of the grasped payload will be included in the simulated arm dynamics. Payload center of mass location will be available in terms of a vector from the terminal device to the

mass center. Thus, the shuttle/manipulator/payload with the aforementioned approximations is a constrained system of four (or five) rigid masses with at least twelve degrees of freedom. It is not clear at this time to what further extent the dynamics problem can be simplified. Certain simplifications can apparently be ruled out, however. Since the system can deploy payloads approximately 1/3 as massive as the shuttle, and since the arm may be useful to provide forces during the final phase of shuttle-to-shuttle docking, the mass of the shuttle cannot be approximated as infinitely large with respect to the grasped payload. Hence, the interaction of the manipulator dynamics with shuttle dynamics must be simulated. Since the arm, during deployment, retrieval, and docking, will brake relative velocities between the shuttle vehicle and massive objects, arm position will not necessarily follow input commands except over very long periods of time. Thus, no such simplifying assumptions may be made. Application of torque to a given joint will either cause motion at other joints, or require opposing torques at other joints. Hence, the dynamics of a given joint cannot be simulated in isolation from other joints (except possibly as a temporary approximation). Joints are provided for motion about all three axes, so planar simplifications are not possible. The effects of joint brakes and position limits on each joint will be included in the arm dynamics simulation. The arm dynamics will reflect the effects of forces and torques (external to the payload system) on the shuttle vehicle and shuttle vehicle angular velocity. The arm dynamics simulation will obtain from these inputs, as well as joint torques and previous manipulator state, the angular accelerations on each joint. These accelerations will be integrated to obtain joint velocities and positions, force and torque exerted by the manipulator upon the shuttle vehicle, orientation of the wrist beam upon which the TV camera and floodlight is mounted, and orientation of the grasped payload, if any. Collision constraints will be simulated. The positions of the elbow joint, wrist joint, and payload (or terminal

device if unloaded) will be calculated from the joint angles. The payload will be approximated as a cylindrical solid. All three beams and the payload (or terminal device) will then be checked to insure they are not in collision with any part of the shuttle vehicle, a payload, or another arm. If a collision has occurred, the necessary joint angles will be reset and joint rates zeroed to prevent the manipulator/payload from penetrating the vehicle. Accurate simulation of collision dynamics is not assumed to be necessary for training simulation. Since the operator should be trained to avoid smashing the manipulator/payload into the vehicle, it would appear that only the detection of collision must be simulated accurately. Outputs of the joint potentiometers and tachometers are calculated from the true joint positions and velocities. These outputs will also reflect instrument biases and malfunctions, as well as quantization. An iteration rate of 10 per second is applied to the manipulator simulation. This rate should be within the limits of perception, and, with a high fidelity dynamics simulation, should provide adequate response characteristics accuracy. As the real-world on-board computer data interface rate is not currently known, it has not been taken into account. If computer interface rates are considerably higher than this, which is possible, it should be possible to obtain adequate approximations to the outputs to the computer during the interval between arm dynamics recalculation times. Since system performance characteristics appear to be quite sluggish, such approximations are not expected to cause severe degradation of system response characteristics. The conceptual design for the manipulator simulation is sketched in figure 4.3.10.2-1.



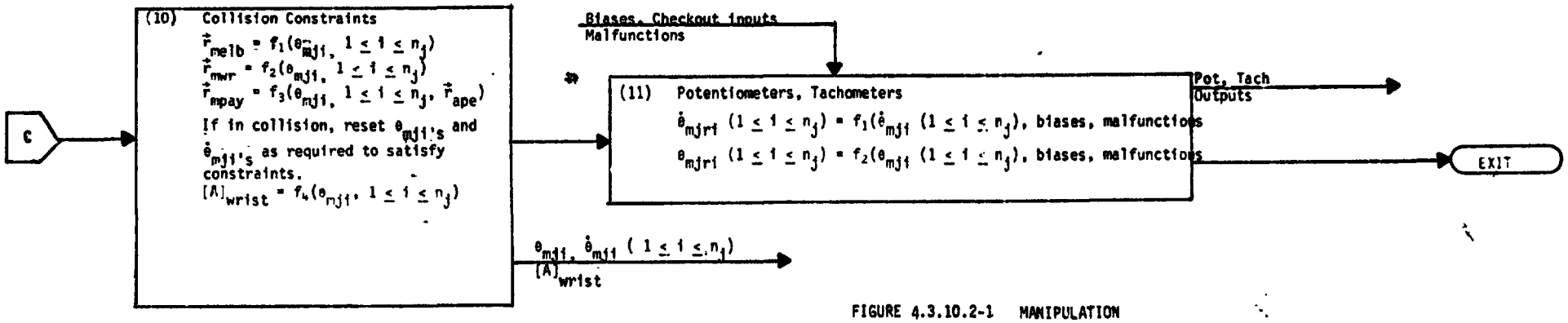

C
(10) Collision Constraints
$\vec{r}_{melb} = f_1(\theta_{mji}, 1 \le i \le n_j)$
$\vec{r}_{mwr} = f_2(\theta_{mji}, 1 \le i \le n_j)$
$\vec{r}_{mpay} = f_3(\theta_{mji}, 1 \le i \le n_j, \vec{r}_{ape})$
If in collision, reset θ_{mji}'s and $\dot{\theta}_{mji}$'s as required to satisfy constraints.
$[A]_{wrist} = f_4(\theta_{mji}, 1 \le i \le n_j)$
Biases, Checkout inputs
Malfunctions
(11) Potentiometers, Tachometers
$\dot{\theta}_{mjri}$ $(1 \le i \le n_j) = f_1(\dot{\theta}_{mji}$ $(1 \le i \le n_j)$, biases, malfunctions
θ_{mjri} $(1 \le i \le n_j) = f_2(\theta_{mji}$ $(1 \le i \le n_j)$, biases, malfunctions
Pot, Tach Outputs
EXIT
$\theta_{mji}, \dot{\theta}_{mji}$ $(1 \le i \le n_j)$
$[A]_{wrist}$

FIGURE 4.3.10.2-1 MANIPULATION

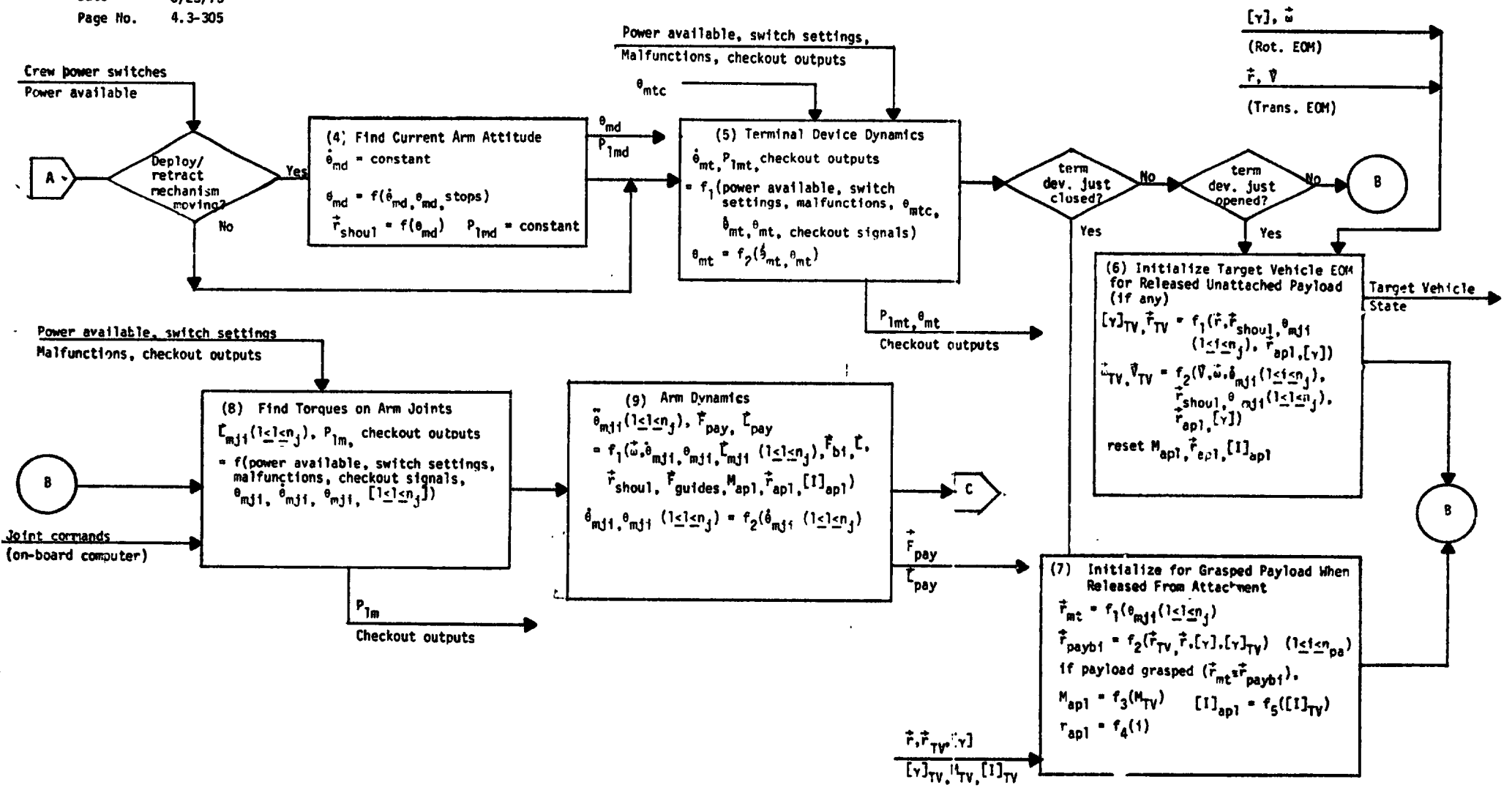

Crew power switches
Power available
A
Deploy/ retract mechanism moving?
Yes
No
(4) Find Current Arm Attitude
$\dot{\theta}_{md}$ = constant
$\theta_{md} = f(\dot{\theta}_{md}, \theta_{md}, \text{stops})$
$\vec{r}_{shoul} = f(\theta_{md})$ P_{1md} = constant
θ_{md}
P_{1md}
Power available, switch settings, Malfunctions, checkout outputs
θ_{mtc}
(5) Terminal Device Dynamics
$\dot{\theta}_{mt}, P_{1mt}$, checkout outputs
$= f_1$(power available, switch settings, malfunctions, θ_{mtc}, $\dot{\theta}_{mt}, \theta_{mt}$, checkout signals)
$\theta_{mt} = f_2(\dot{\theta}_{mt}, \theta_{mt})$
P_{1mt}, θ_{mt}
Checkout outputs
term dev. just closed?
No
Yes
term dev. just opened?
No
Yes
B
[γ], $\vec{\omega}$
(Rot. EOM)
$\vec{r}$, $\vec{v}$
(Trans. EOM)
(6) Initialize Target Vehicle EOM for Released Unattached Payload (if any)
$[\gamma]_{TV}, \vec{r}_{TV} = f_1(\vec{r}, \vec{r}_{shoul}, \theta_{mji} (1 \le i \le n_j), \vec{r}_{apl}, [\gamma])$
$\vec{v}_{TV}, \vec{v}_{TV} = f_2(\vec{v}, \vec{\omega}, \dot{\theta}_{mji} (1 \le i \le n_j), \vec{r}_{shoul}, \theta_{mji} (1 \le i \le n_j), \vec{r}_{apl}, [\gamma])$
reset $M_{apl}, \vec{r}_{apl}, [I]_{apl}$
Target Vehicle State
B
Power available, switch settings
Malfunctions, checkout outputs
B
Joint commands (on-board computer)
(8) Find Torques on Arm Joints
$\tau_{mji} (1 \le i \le n_j)$, P_{1m}, checkout outputs
= f(power available, switch settings, malfunctions, checkout signals, $\theta_{mji}, \dot{\theta}_{mji}, \ddot{\theta}_{mji}, [1 \le i \le n_j]$)
P_{1m}
Checkout outputs
(9) Arm Dynamics
$\ddot{\theta}_{mji} (1 \le i \le n_j)$, $\vec{F}_{pay}$, τ_{pay}
$= f_1(\vec{\omega}, \dot{\theta}_{mji}, \theta_{mji}, \tau_{mji} (1 \le i \le n_j), \vec{F}_{bi}, \tau_i, \vec{r}_{shoul}, \vec{F}_{guides}, M_{apl}, \vec{r}_{apl}, [I]_{apl})$
$\dot{\theta}_{mji}, \theta_{mji} (1 \le i \le n_j) = f_2(\dot{\theta}_{mji} (1 \le i \le n_j)$
C
$\vec{F}_{pay}$
τ_{pay}
(7) Initialize for Grasped Payload When Released From Attachment
$\vec{r}_{mt} = f_1(\theta_{mji} (1 \le i \le n_j)$
$\vec{r}_{paybf} = f_2(\vec{r}_{TV}, \vec{r}, [\gamma], [\gamma]_{TV})$ $(1 \le i \le n_{pa})$
if payload grasped ($\vec{r}_{mt} = \vec{r}_{paybf}$),
$M_{apl} = f_3(M_{TV})$ $[I]_{apl} = f_5([I]_{TV})$
$r_{apl} = f_4(1)$
$\vec{r}, \vec{r}_{TV}, [\gamma]$
$[\gamma]_{TV}, M_{TV}, [I]_{TV}$

FIGURE 4.3.10.2-1 Page 2

Symbol Dictionary for Figure 4.3.10.2-1

$[A]_{wrist}$	Wrist orientation matrix	P_{lmt}	Power load due to terminal device operation
$\vec{F}_{bi}$	Body forces on shuttle vehicle (inertial coordinates)	$\vec{r}$	Shuttle position
$\vec{F}_{guides}$	Force due to payload attachment guides	$\vec{r}_{arm}$	Position of jettisoned arm
$\vec{F}_{pay}$	Force exerted on shuttle vehicle by manipulator arm	$\vec{r}_{apl}$	Terminal device to payload mass center vector
$[I]_{apl}$	Inertia tensor of attached payload	$\vec{r}_{melb}$	Position of arm elbow
$[I]_{tv}$	Target vehicle inertia tensor	$\vec{r}_{mpay}$	Position of arm payload
$\vec{L}$	Total moment on shuttle vehicle	$\vec{r}_{mwr}$	Position of arm wrist
$\vec{L}_{mji}$	Torque on i^{th} arm joint	$\vec{r}_{paypi}$	Position of i^{th} payload grasping point
$\vec{L}_{pay}$	Total moment exerted on shuttle vehicle by manipulator arm	$\vec{r}_{shoul}$	Position of arm shoulder
M_{apl}	Mass of attached payload	$\vec{r}_{snapties}$	Positions of arm latching snap ties
M_{tv}	Mass of target vehicle	$\vec{r}_{tv}$	Target vehicle position
n_j	Number of manipulator arm degrees of freedom	$\vec{V}$	Shuttle velocity
n_{pa}	Number of payload grasping points	$\vec{V}_{arm}$	Velocity of jettisoned arm
P_{lm}	Power load due to arm operation	$\vec{V}_{tv}$	Target vehicle velocity
P_{lmd}	Power load due to deployment device operation	$[\gamma]$	Shuttle direction cosines
		$[\gamma]_{tv}$	Target vehicle direction cosines
		θ_{door}	Payload door angular position
		θ_{md}	Deployment device angle

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$\dot{\theta}_{md}$	Deployment device angular rate
θ_{mji}	Position of i^{th} manipulator arm angle
$\dot{\theta}_{mji}$	Angular rate of i^{th} manipulator arm angle
$\ddot{\theta}_{mji}$	Angular acceleration of i^{th} manipulator arm angle
θ_{mjci}	Commanded position of i^{th} manipulator arm angle
θ_{mjri}	Readout of i^{th} joint potentiometer
$\dot{\theta}_{mjri}$	Readout of i^{th} joint tachometer
θ_{mt}	Position of terminal device angle
$\dot{\theta}_{mt}$	Angular rate of terminal device angle
θ_{mtc}	Commanded position of terminal device angle
$\vec{\omega}$	Shuttle vehicle angular rate
$\vec{\omega}_{tv}$	Target vehicle angular rate

4.3.10.3 Payload Bay Doors Subsystem

The payload door simulation calculates the position of each segment of the payload doors and space radiators, torques exerted on the shuttle vehicle by their motion, their effects upon vehicle mass properties and hydraulic flow. When unlatched and in motion, proximity of the doors to the appropriate latch proximity sensors will be checked on each pass through the program. When proper proximity is achieved (and switches, breakers, power, etc., are properly configured), the latches will be actuated. Latch zip-fastener action will be simulated as a function of time since the proximity sensors were actuated. Door motion will be simulated both with and without space radiators attached. Door motion will take place only when necessary electrical and hydraulic power are available and it is commanded. The angle between the door position when closed and the current door position (measured in the plane normal to the door longitudinal centerline) as well as the angle between the space radiator position when closed and the current space radiator position will be maintained. When in motion, the door will move at an angular rate which is a function only of hydraulic flow available. (No data on door motion is available, but this seems to be a reasonable assumption). The current door and radiator angles will be used to calculate door and radiator center of mass positions and inertia sensors in the shuttle B coordinate frame, for use in shuttle mass properties. When in accelerated motion, the doors will exert a reaction torque on the shuttle vehicle. The real-world door/vehicle dynamics problem is fairly complex, due to the continual vehicle inertia change during door motion. The torques involved in closing both door/radiator combinations (worst case) are internal to the shuttle body, and do not affect the total angular momentum of the system. Thus, system angular momentum should remain constant during the operation. Hence, as the doors/radiators open, since the inertia tensor decreases, shuttle body rates increase to conserve angular momentum. However, other torques (e.g., RCS firings) could alter

angular momentum during this interval. The total resulting dynamics could be simulated with high precision, but the simulation would not be simple. The dynamics could probably be approximated somewhat more simply, but less accurately. Or, the effect could be ignored. Considering that, during door closing, body rates should ordinarily be low, and that door/radiator mass is probably a fairly small fraction of vehicle mass, and therefore will not unduly affect inertia tensor, and that these dynamics should not involve any important crew cues, it is currently intended to ignore them. If any of the above assumptions are violated as design and procedures development advances, the above conclusion should be altered. The payload door simulation will be iterated 10 times per second, the same rate as most of the remainder of the payload accommodation system. This rate should be sufficient to provide training cues to within the perception of the crew. The conceptual design of the simulation for a given segment is sketched in figure 4.3.10.3-1.

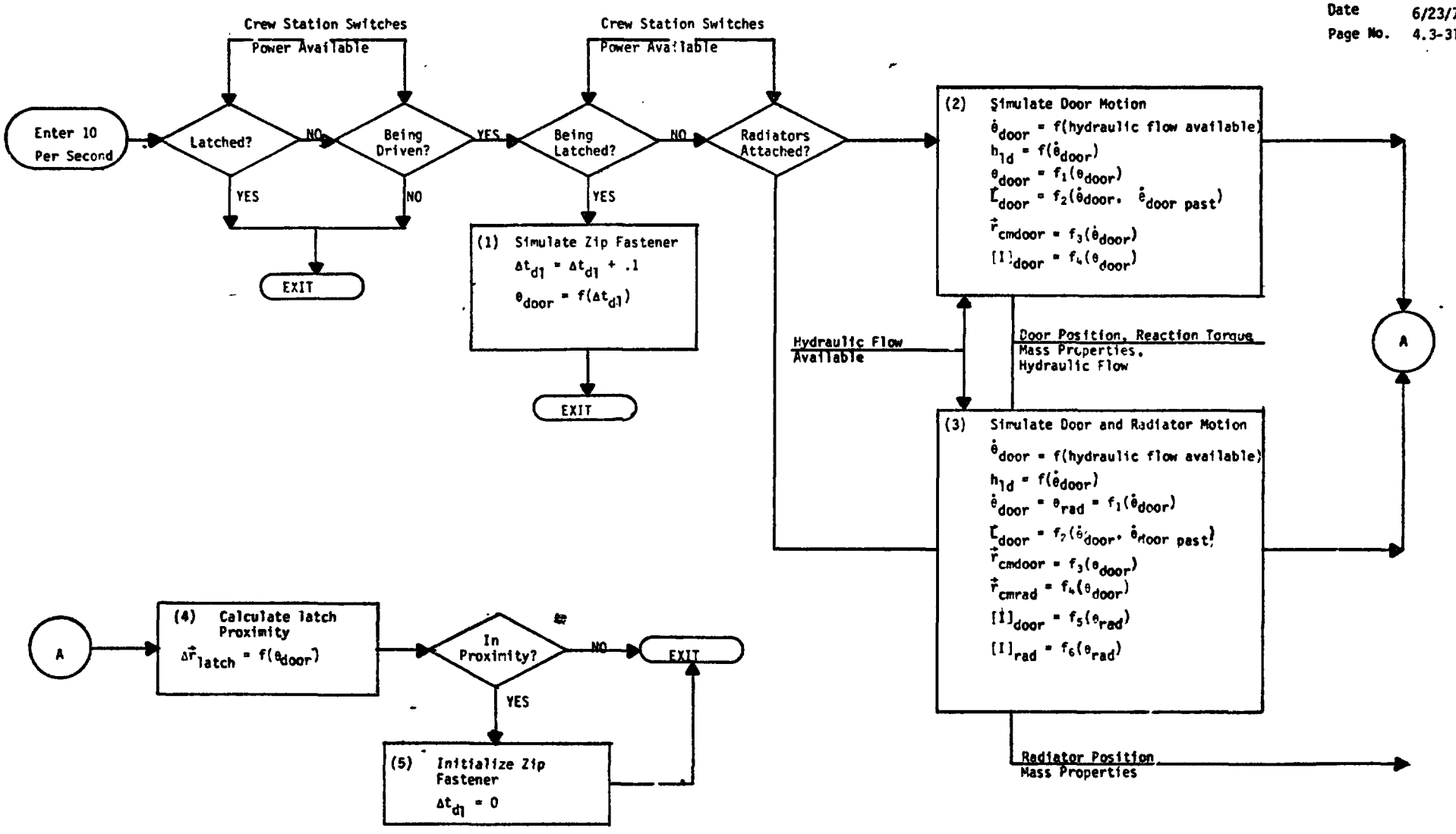


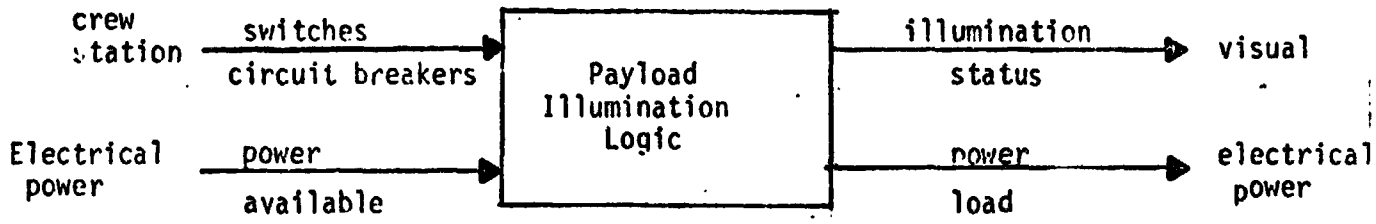
FIGURE 4.3.10.3-1 PAYLOAD BAY DOORS

Symbol Dictionary for Figure 4.3.10.3-1

$[I]_{door}$	Current inertia tensor of payload door (shuttle B coordinates)
$[I]_{rad}$	Current inertia tensor of space radiator (shuttle B coordinates)
$\dot{\vec{L}}_{door}$	Reaction torque on shuttle due to accelerated door motion
$\vec{r}_{cmdr}$	Current mass center of payload door (shuttle B coordinates)
$\vec{r}_{cmrad}$	Current mass center of space radiator (shuttle B coordinates)
$\vec{\Delta r}_{latch}$	Vector from door latch point to proximity sensor
Δt_{de}	Time since latching initiated
θ_{door}	Angular position of door with respect to shuttle
$\dot{\theta}_{door}$	Angular rate of door with respect to shuttle
θ_{rad}	Angular position of radiator with respect to shuttle

4.3.10.4 Payload Illumination Subsystem

The simulated payload bay illumination subsystem will determine whether each of the payload bay lights are lit, and calculate the resulting power loads. The appropriate crew station switches and breakers, as well as the appropriate power available boolean, will be checked to determine whether each light is on. Each illuminated light will provide a characteristic constant increment to the total power load from the payload illumination subsystem. The illumination status of each light will be provided to the simulated visual system.



4.3.10.5 Payload TV Subsystem

The simulated payload bay television subsystem will determine whether each of the payload bay television cameras are in operation, calculate the orientation of all moveable cameras, determine whether each of the payload handling station television monitors is in operation, and calculate the resulting power loads. A camera will be simulated as on when the appropriate crew station switches, crew station circuit breakers, and power available booleans exhibit the correct configuration. Each operating camera or monitor will provide an increment to the total power load from the payload bay television subsystem. The operational status of each camera and monitor will be provided to the simulated visual subsystem. The orientation of the manipulator arm wrist TV cameras will be calculated from data received

from the simulated payload manipulators. Orientation of other moveable attitude cameras will be calculated from crew station switch inputs (taking due account of power available), and manipulator orientation if an automatic track capability exists. The same television logic will be used to simulate other on-board television systems.

Symbol Dictionary

$[A]_{wrist}$	Manipulator wrist axes to body axes direction cosines
l_{camonj}	j^{th} tv camera on/off
l_{mononj}	j^{th} tv monitor on/off
$\vec{l}_{cam}$	Direction of center of camera field of view
$\vec{j}_{cam}$	Direction of camera Vertical axis
n_c	Number of tv cameras
n_j	Number of manipulator joints
n_m	Number of tv monitors
P_{lptv}	Payload tv system power load
$\vec{r}_{cam}$	Position of camera
θ_{mji}	Position of i^{th} manipulator joint

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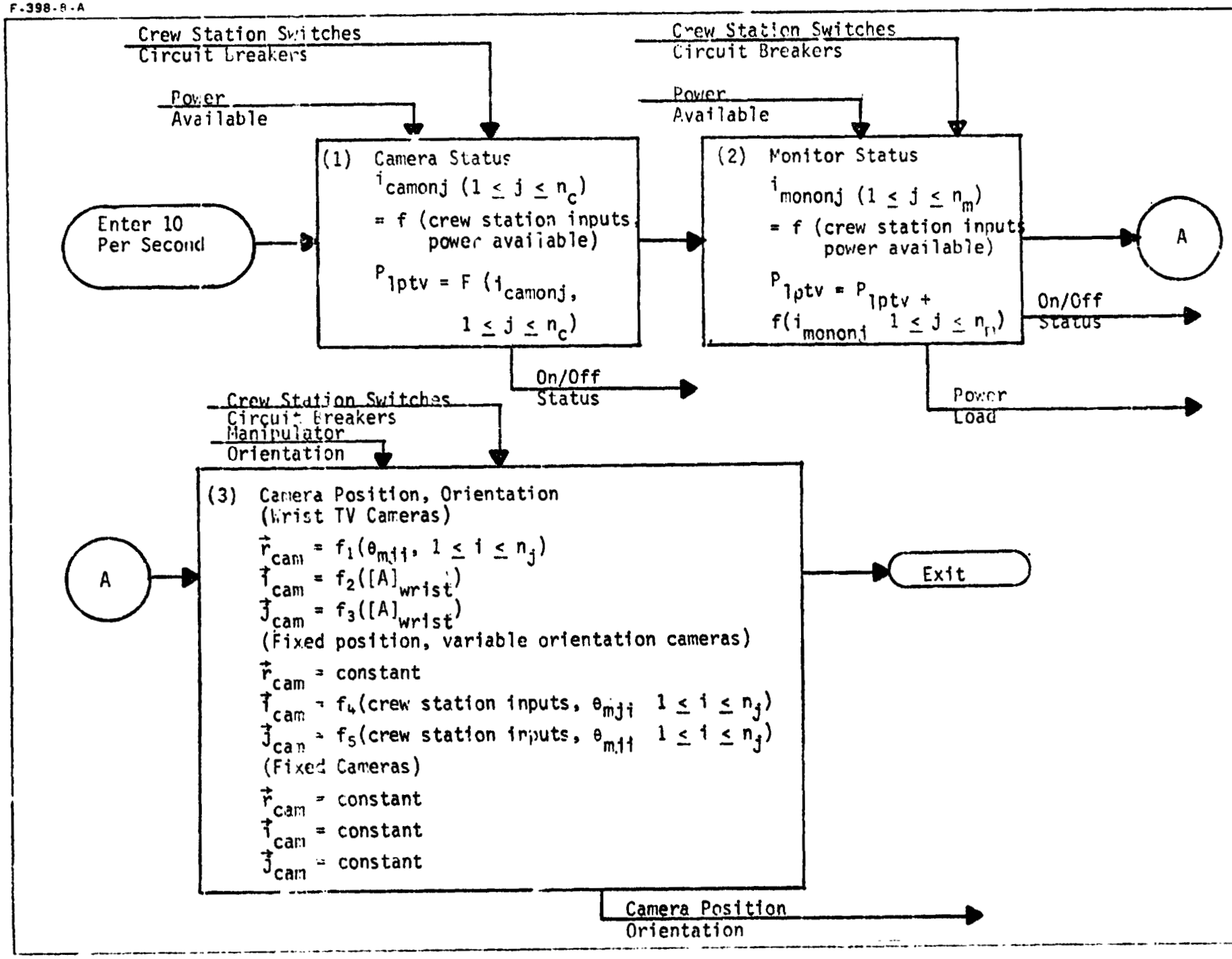

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4.4 System Software Conceptual Design

4.4.1 Simulator Control Software

4.4.1.1 Data Recording

The data recording routines will output internal simulation data values in a format usable by the instructor for trainee evaluation and debriefing. There are three main data recording routines.

4.4.1.1.1 X-T Recorders

This routine reformats and rescales internal data values into analog output signals usable by a standard X-T strip recorder. The parameters processed by this routine will be selectable by a CRT page.

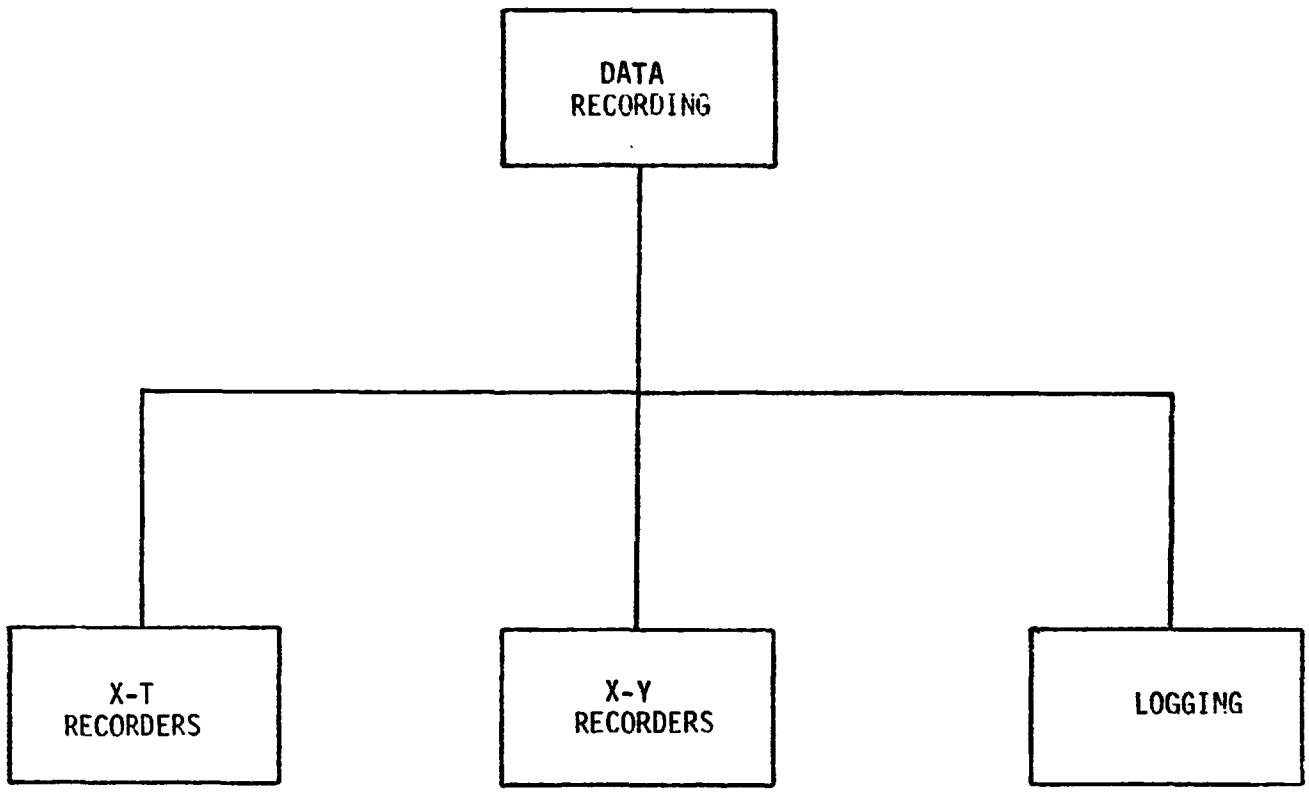
4.4.1.1.2 X-Y Recorders

This routine reformats and rescales two internal parameters and generates analog output signals, allowing a standard X-Y plotter to plot one parameter versus another. The parameters processed by this routine will be selectable by a CRT page.

4.4.1.1.3 Logging

This routine outputs, at a minimum 20/sec. rate, raw parameter values, along with header and formatting information. This output will be placed on magnetic tape in a form usable by an off-line routine which will produce hard copy listings of the parameters. The recording rate of the parameters, as well as the identification of the parameters, will be selectable by a CRT page.

FIGURE 4.4.1.1-1 DATA RECORDING



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4.4.1.2 Real-Time Input/Output

The real-time input/output routines are responsible for transferring data between the simulator data pool and the DCE mini-computers. Additionally, the RTIO will maintain the data flow to MCC, and output the telemetry down link data. Thus, the RTIO may be viewed as containing seven separate functions.

4.4.1.2.1 Digital Input

This routine will input discrete data bits from switch-type devices. These inputs will be accepted in an unpacked form from the DCE mini-computer.

4.4.1.2.2 Analog Input

This routine will input data from analog devices. This data will be converted to host computer floating point format by the DCE mini-computer.

4.4.1.2.3 MCC Input

When integrated with MCC, this routine receives the interface data, verifies correctness, and presents the data to the simulation routines.

4.4.1.2.4 Digital Output

This routine will output discrete data bits to lamp and readout-type devices in the form of one bit per computer word. The DCE mini-computer will be responsible for packing the data for the linkage.

4.4.1.2.5 Analog Output

This routine will output data to be displayed on meter-type devices. This data will be output in host computer floating point format to the DCE mini-computer which will convert it to DCE acceptable format.

4.4.1.2.6 MCC Output

When integrated with MCC, this routine will collect data from the simulation routines, format the data, provide check sums, and ouput the interface data to MCC.

4.4.1.2.7 Telemetry Output

When integrated with a complex that requires telemetry data from SMS, this routine will collect the data from the simulation routines, format it, and output the data to that complex.

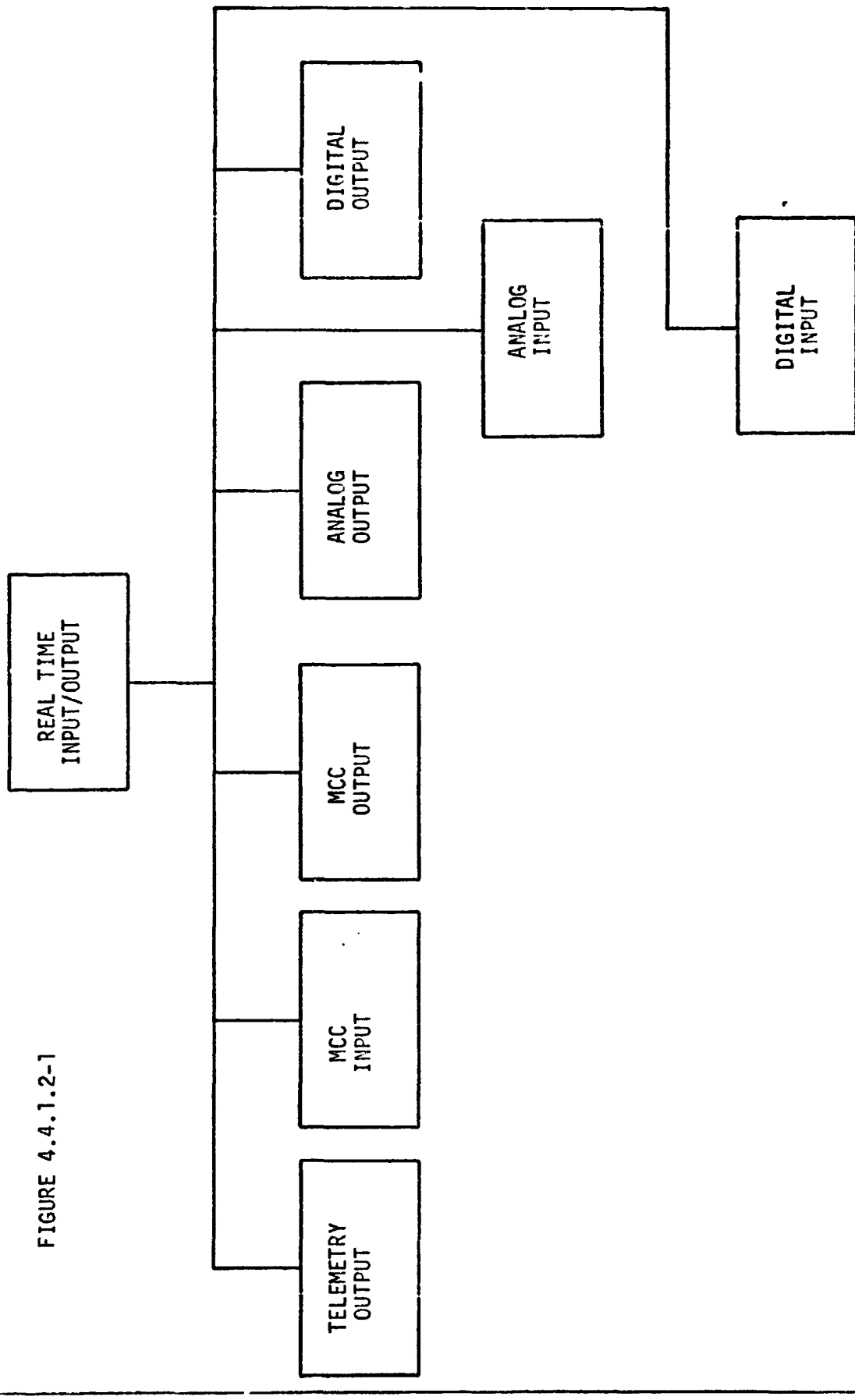

FIGURE 4.4.1.2-1

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4.4.1.3 Synchronous Simulation Program Processor (SSPP)

This package serves as the focal point for the execution of the software modules that must execute in a cyclic manner.

The basic jump list management functions incorporated in conventional simulation packages are handled by this module. Thus, program sequencing and iteration rates are a matter of position within the jump list.

In addition to the module address, each element of the jump list will contain flags indicating for which mission phase the module is required. If the module is not required during the current mission phase, it will not be executed.

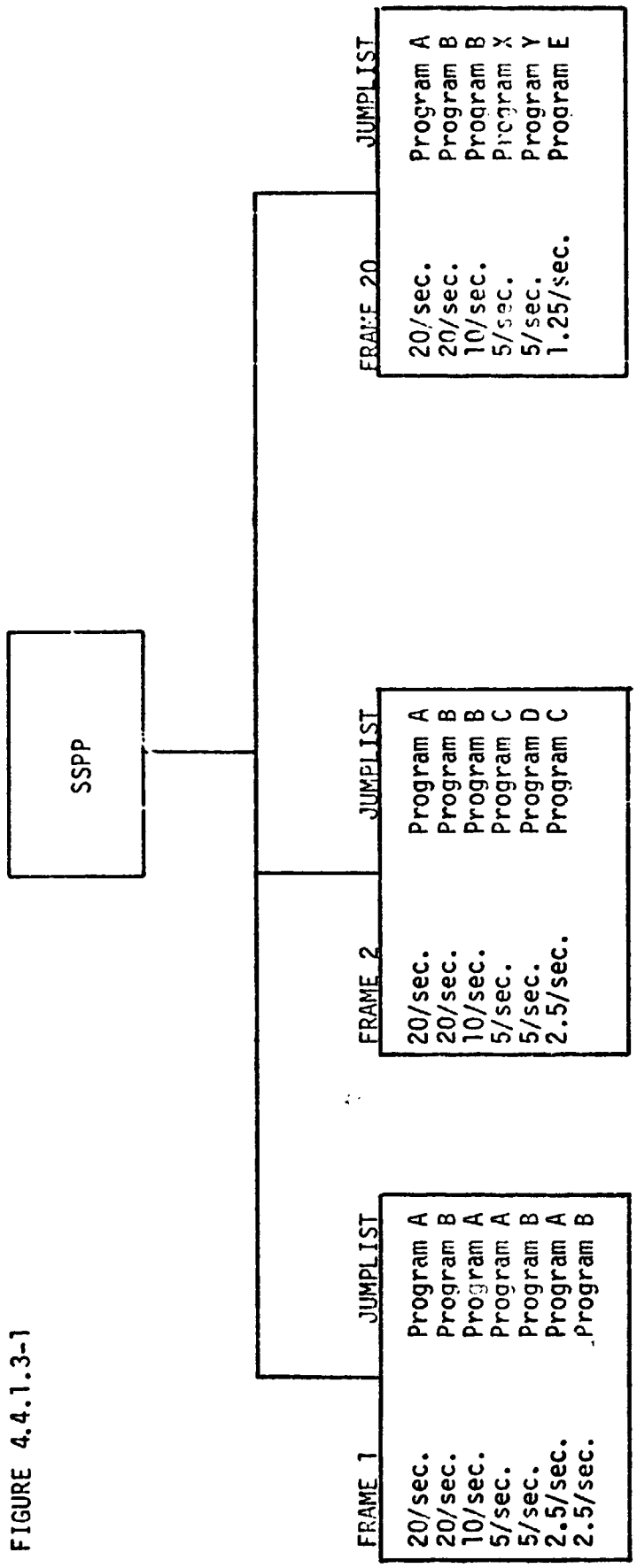

FIGURE 4.4.1.3-1

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4.4.1.4 Master Timing

The master timing routine is respoinsible for maintaining the correct time references for the simulator. This includes maintenance of simulated Greenwich Mean Time, simulated Mission Elapsed Time, simulation clocks, event timers, and any special time words (for syncing with MCC, DCS, TM, etc.).

Output data compatible with any computer driven time displays will be generated by master timing.

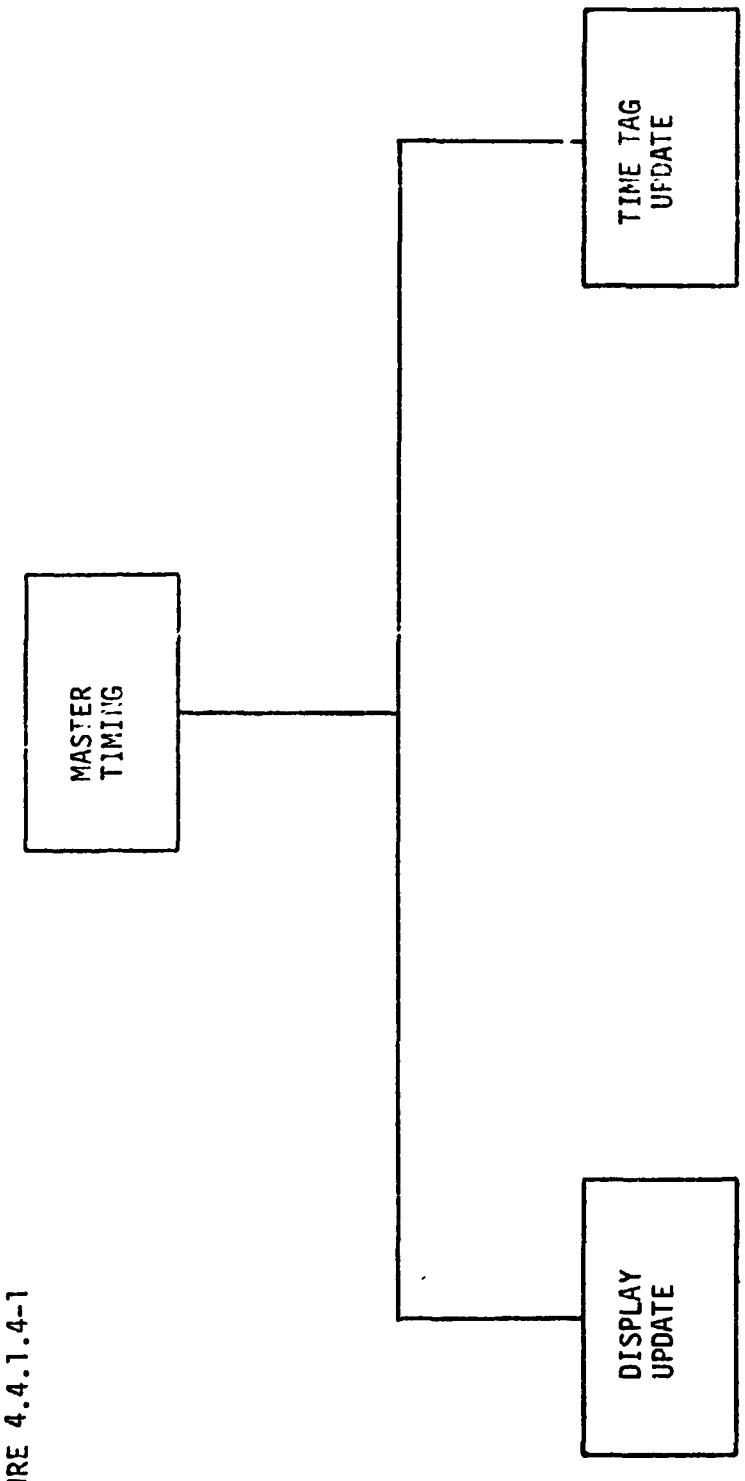

FIGURE 4.4.1.4-1

4.4.1.5 Master Control

The master control program will provide the instructor-operators with the capability of controlling the simulation exercise. This program will respond to switch inputs actuated by the instructor-operators and will provide feedback so that the simulator mode will always be displayed to the instructors.

The following simulator modes will be provided for in the master control program.

4.4.1.5.1 OPERATE

This is the "normal" or operational mode of the simulator. When in "OPERATE," all real-time software is executed and all time constants or integration delta times are set at their real-time values.

4.4.1.5.2 FREEZE

This is the "stop action" mode in which all real-time software is executed, but all integration delta times are set to zero. In this manner, all logic equations and all computations not affected by time are executed, but the simulator's problem is "frozen" in time.

4.4.1.5.3 RESET

This mode provides a means of initializing all reset parameters in the simulator. The initialization data will be read into core memory upon request from the instructor. The instructor will use the CRT keyboard to specify the reset point number.

4.4.1.5.4 WRITE RESET

This mode will cause "a snapshot" of initialization data and this information will be written on mass storage. The reset point identifier and the initialization data will be written on mass storage when the instructor-operator

requests this function via a CRT page. This function will be operational in the "OPERATE" or "FREEZE" mode.

4.4.1.5.5 SAFE STORE

This mode (when enabled) will provide a means of automatically generating a set of initialization points on a time basis. One initialization point will be generated every ten minutes in this mode. A CRT displayable record identifying each point will be saved as each point is transferred from core to mass storage. This record will provide the instructor with a means of identifying a particular "SAFE STORE" point and returning to it via the "RESET" function.

4.4.1.5.6 STEP-AHEAD

This mode will provide a means of accelerating the simulation through periods of trainee inactivity in faster than real-time. The vehicle will remain in an inertial hold mode and simply translate through time at a minimum of ten times real-time. This mode will be activated by entering the delta time necessary to reach desired mission time via the CRT keyboard. When the desired time has been reached, the simulator will automatically switch from the "STEP-AHEAD" mode to the "FREEZE" mode.

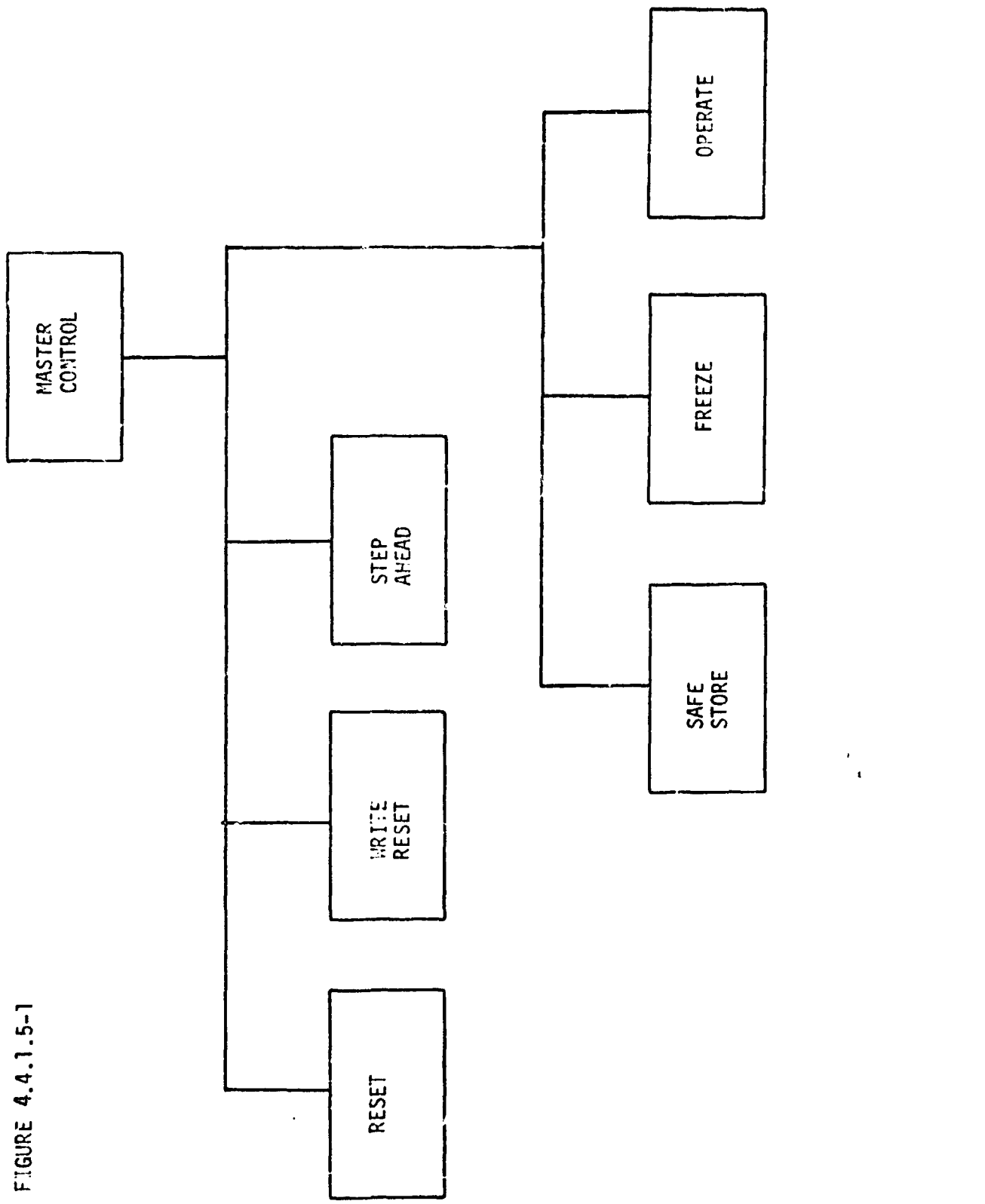

FIGURE 4.4.1.5-1

4.4.1.6 Record Playback

This system will, when not disabled by the instructor, continually record trainee activity. This recording shall include at least the last ten minutes of activity performed by the trainee.

The record playback system will record, on disk storage, selected inputs, outputs, and internal simulation parameters. This data, when input to the simulation programs, will cause the trainer and IOS instruments, readouts, indicators, motion base, and visual to reproduce their activity as it occurred during the period of recording.

There are four principal elements to this system.

4.4.1.6.1 Exercise Recorder

This routine allows internal simulation data values to be recorded on mass storage. The parameters to be recorded will be those that allow student activities to be faithfully reproduced. This routine will also contain control logic to monitor the recording, supply indications relating to recording time remaining, etc.

4.4.1.6.2 Exercise Playback

This routine causes the data recorded by the exercise recorder routine to be reinserted into the simulation data pool. This routine will contain control logic to monitor the playback and, when the playback is complete, insure that all primary controls are in a position to allow a safe flyout from this point.

4.4.1.6.3 Pack/Unpack

During recording, this routine gathers the simulation data values to be recorded and packs them into an output buffer. Booleans are packed into whole words for maximum recording density. During playback, the recorded values are unpacked and restored to their proper location in the data pool.

4.4.1.6.4 Inout/Outout

This routine handles all I/O to the mass storage device(s) used to contain the recorded data This routine will also form check sums to insure the integrity of data transferred.

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4.4.1.7 CRT Pages

"CRT PAGES" is the generic name for all software processed by the CRT off-line processor that will be executed during the real-time simulation. Although there can be many different types of CRT pages available in real-time, it is felt that these pages will fall into seven general classes:

4.4.1.7.1 Panel Pages

These displays represent physical crew station panels; switches, lights, readouts and meter outputs on the crew station panel are repeated on panel pages.

4.4.1.7.2 Malfunction Pages

These pages are used to introduce malfunctions into the simulation problem. Additionally, the pages build internal tables which allow a malfunction page to "remember" what malfunctions are in the simulation problem.

4.4.1.7.3 Special Purpose Pages

These pages provide "one of a kind" displays. Examples of this type of page would include the event time monitor (which monitors crew station switch and analog inputs and will display to the instructor the occurrence of any crew activity), and the tripped circuit breaker page.

4.4.1.7.4 Utility Pages

These pages serve as a communications media between the instructor and the principal control and display routines in the simulator. Functions such as reset, step-ahead, write-reset are controlled by utility pages. The parameters monitored by the X-T, X-Y, and logging routines may be changed by utility pages.

4.4.1.7.5 Engineering Support Pages

The engineering support pages constitute perhaps the largest group of pages. These pages are useful in performing a detailed analysis of a simulated system. Depending upon how they are programmed, elements from each of the above classes of pages may be included in a support page.

4.4.1.7.6 External Interface Pages

These pages display the interface data streams between the "Spacecraft" and the "Ground". The telemetry downlink and DCS uplink data streams will be displayable by these pages. Any additional data streams that may be unique to an integrated simulation will also be displayable by this type of page.

4.4.1.7.7 Crew Station Setup and Verification (CSSUV) Pages

These pages provide for rapid checkout and verification of crew station controls. Each CSSUV page will inspect a section of the crew station and compare those controls against a pre-defined 'DESIRED' value, indicating to the instructor which controls are not physically in the desired position. When the controls are set in accordance with the desired positions, the CSSUV page will 'MOVE ON' to the next page in sequence.

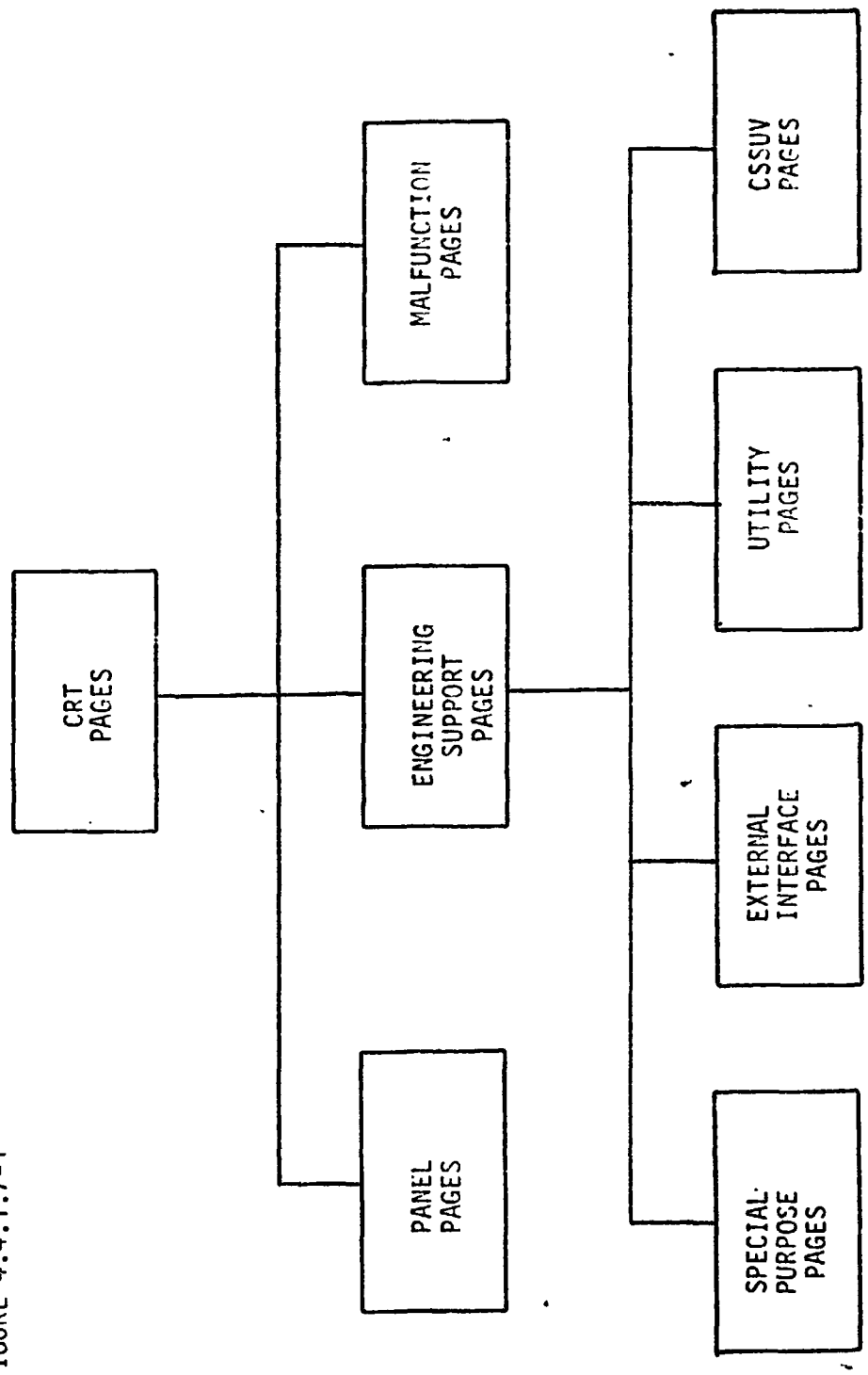

FIGURE 4.4.1.7-1

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4.4.1.8 CRT Interactive Processor

The CRT interactive processor supports two prime functions: execution of CRT page programs and CRT keyboard entry. Each function is delineated below:

4.4.1.8.1 Cyclic Routines

These routines directly support the CRT page programs, thus they execute in a cyclic fashion. The prime routines of interest are:

4.4.1.8.2 Top Line Processor

This routine is responsible for maintenance of the top line display on all CRT's. This maintenance will include updating of mission times, ground station contact, etc.

4.4.1.8.3 Page Executive

The CRT page programs are executed under control of this routine. The page executive also performs the final linkage between the relocatable CRT page and the common data pool.

4.4.1.8.4 Look and Enter

This routine will maintain correct value displays on any screen which has an active look and enter request.

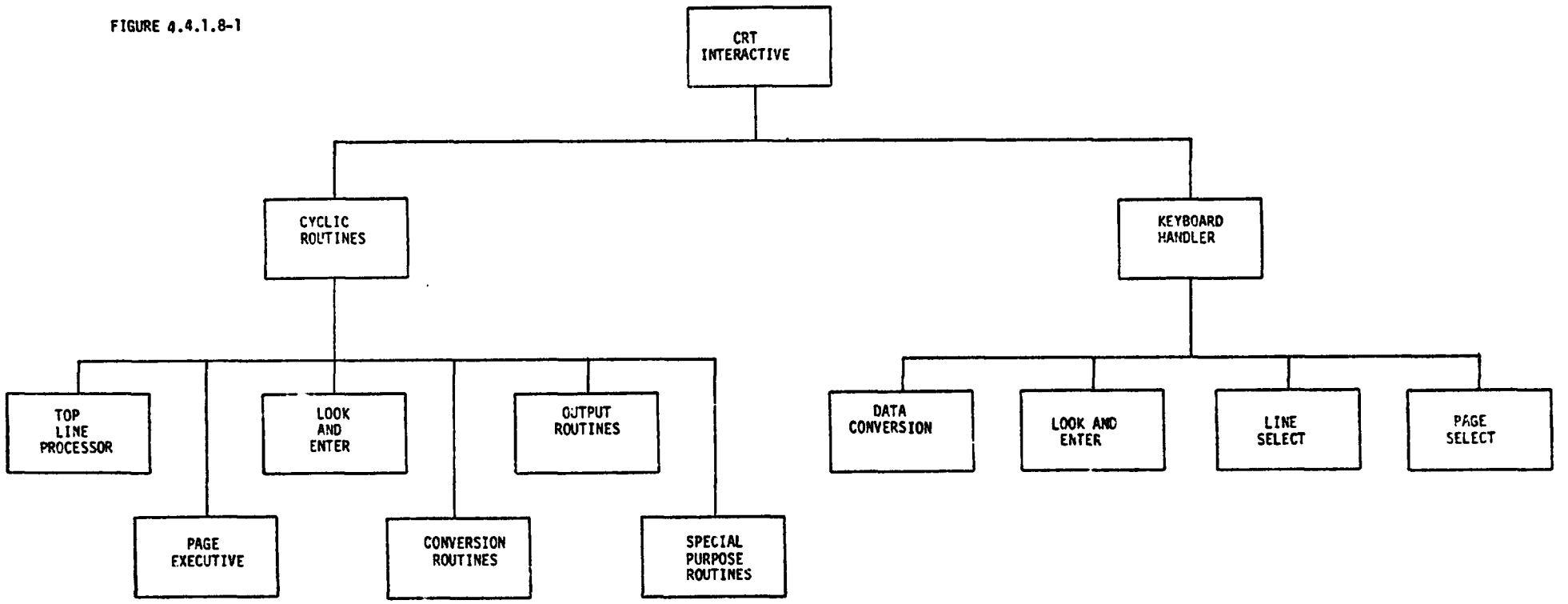
4.4.1.8.5 Conversion Routines

These routines convert the computer binary data to a form displayable on the CRT screen. Possible types of conversion will include hexadecimal, octal, floating point, integer, and binary.

4.4.1.8.6 Output Routines

These routines cause the CRT display to be transferred to the CRT hardware.

FIGURE 4.4.1.8-1



4.4.1.8.7 Special Purpose Routines

These routines interface with the CRT pages described in 4.4.1.7.3, and provide the very specialized functions required to support those pages. The routines involved in this area will include an event time monitor processor, a tripped circuit breaker processor, and a circuit breaker malfunction processor for use by the panel pages.

4.4.1.8.8 Keyboard Support

These routines respond to CRT keyboard input and perform the required actions to complete the request. Examples of these routines will include:

4.4.1.8.8.1 Page Select

This routine will search a catalog of available CRT pages and load the selected page if found.

4.4.1.8.8.2 Line Select

This routine will scan tables built by the CRT off-line processor and will build a scratch pad line entry for all defined input fields.

4.4.1.8.8.3 Look and Enter

This routine allows the instructor to view and/or modify any data pool parameter, by name, independent of any CRT page displayed on the CRT screen.

4.4.1.8.8.4 Data Conversion Routines

These routines accept as input CRT keyboard characters and convert them into computer binary numbers. The conversion types will include hexadecimal, octal, integer, Boolean, and floating point data.

4.4.1.9 Simulation Software Structure

The four representative mainframe configurations are presented in section 3.2.5.3 of this document. This section will describe four software structures, one per configuration, that may be used to perform the required simulation task.

4.4.1.9.1 General Design Requirements

In order to arrive at any simulation software structure, there are several general requirements that must be made. This section will delineate the major requirements applicable to all the simulation software structures.

4.4.1.9.1.1 Programming Language

The majority of the simulation software will be programmed in FORTRAN, or a higher level language. The software that cannot be programmed in a high level language due to the nature of the functions to be performed will be programmed in the assembly language of the computer.

4.4.1.9.1.2 The Operating System

The Operating System will provide a hospitable environment for the required real-time simulation software and can provide all required services. These services will be delineated elsewhere in this report.

4.4.1.9.1.3 Iteration Rates

Each discrete module of the simulation software will require iteration (recurrent execution) at one of the following rates: 20, 10, 5, 2, or 1 times per second.

4.4.1.9.1 4 Asynchronous Event Synchronization

The processing of an asynchronous event can be performed synchronously, (i.e., input elements can be accumulated at random intervals

(asynchronously) and, at some point, processing for the total input group can be initiated and synchronized with other cyclic activities.

4.4.1.9.1.5 Input/Output

A request for I/O does not cause the requesting activity to relinquish either execution control or computer resources until the I/O is complete.

4.4.1.9.1.6 Programming Considerations

The OS environment and services provided for real-time mode will be such that the simulation programmer can dedicate himself to the actual simulation problem and be relieved of recreating or duplicating OS functions wherever possible.

4.4.1.9.1.7 Structure Concepts

Since the Shuttle Mission Simulator software, like any other real-time flight simulator, is basically a synchronous entity, a structure must be developed that will insure that this functional format is maintained.

Such a structure implies a capability for independently programming separate modules and later collecting them into a single entity for execution. It also suggests a capability for global external naming (labeling) in both the High Level and Assembler elements so that proper inter-module communication can be established.

4.4.1.9.1.8 Data Pool Concepts

The named data values required by the simulation software will fall into two major classes:

- Internal
- External

Internal data values exist within an individual program and are

used only by that program. External data values are shared between several programs.

All external data should be collected into one area freely accessible by all software modules. Since a high level language will be the basic programming language, a named common feature can be used. These named common areas can be organized by simulated system, data type, data function, or by any other method that is convenient.

Since there exist named data value interdependencies between program modules, nonsequential access to the data pool is required.

4.4.1.9.2 Simulation Software Structure in the Univac Configuration

The Univac 1110 configuration consists of four CAU's sharing 262K primary storage and 262K extended storage per crew station, and 2 CAU's sharing 262K primary storage and 131K extended storage.

4.4.1.9.2.1 General Requirements

The following requirements apply directly to the structure definition:

4.4.1.9.2.1.1 CAU Execution Rate

Each CAU is capable of executing at least 1.5 million instructions per second. This rate will include all memory conflicts.

4.4 1.9.2.1.2 Program/CAU Dependency

A direct relationship can exist between a particular program and a particular CAU.

4.4.1.9.2.1.3 Operating Systems

The operating system will be EXEC 8, or an upward compatible system.

4.4.1.9.2.1.4 Execution from Extended Storage

A CAU cannot execute less than 0.6 MIP when the instruction stream comes completely from extended storage.

4.4.1.9.2.1.5 Parallelism

Large portions of the simulation software can be executed in parallel.

4.4.1.9.2.1.6 Serial Execution

When the simulation software must be executed in a serial mode, that software will be executed in one, and only one, CAU. The computational demand does not exceed the limit of 4.4.1.9.2.1.1 or 4.4.1.9.2.1.4 above.

4.4.1.9.2.1.7 External Interrupts

Upon the occurrance of an external interrupt, the operating system will pass control to one unique entry point in the simulation software package.

4.4.1.9.2.1.8 Operating System Size

The operating system will occupy the first 30K words of primary storage.

4.4.1.9.2.2 Structure

4.4.1.9.2.2.1 Basic Structure

The basic software structure for the ^ CAU system is illustrated in Figure 4.4.1.9.2-1. A core memory map is shown in Figure 4.4.1.9.2-2. As can be seen, this approach has no overlay segments. The rationale for this is as follows:

- With the present fixed base core loading, and a maximum transfer rate of 240K words/sec from the drum, no significant reduction in the total core loading could be made.

- To implement a simple overlay structure will require the dedicated use of two high speed drum memories.

4.3.1.9.2.2.2 Jump List Management

4.4.1.7.2.2.2.1 Four CAU Jump List

The simulation software will be organized into four separate jump lists: A, B, C, and D. The occurrance of a program call in any particular jump list will be a function of four constraints:

- The effect of parallelism upon the module.
- The requirement for serial execution.
- Program iteration rate.
- Mission phases for which execution is required.

It is invisioned that the A, B, and C jump lists will contain all 20, 10 and 5/sec modules that execute in all, or almost all, mission phases. Low rate programs that must meet serial dependencies with these modules will be executed from the proper jump list. Inspection of the memory map shows that, where possible, all modules for the "A" jump list are grouped together, the "B" jump list modules are together, as are the "C" modules. Grouping this way will confine most memory contention to the data pool and subroutine area.

The "D" jump list will consist of modules with low iteration rates, or those which are only executed in one or two phases, (e.g., APES). This will allow programs in extended storage to be executed by one CAU. Thus the high overhead of execution from extended storage is isolated in one CAU, which allows easier control of the loading.

Extended storage will also contain the large, low access tables, (e.g., RADIO ALT. MAP) which have limited use dur g the simulation session. High access tables, (e.g., AERO DATA), will remain in primary storage to eliminate memory delays.

4.4.1.9.2.2.2.2 Two CAu Jump List

These jump lists will be similar to the ones described above.

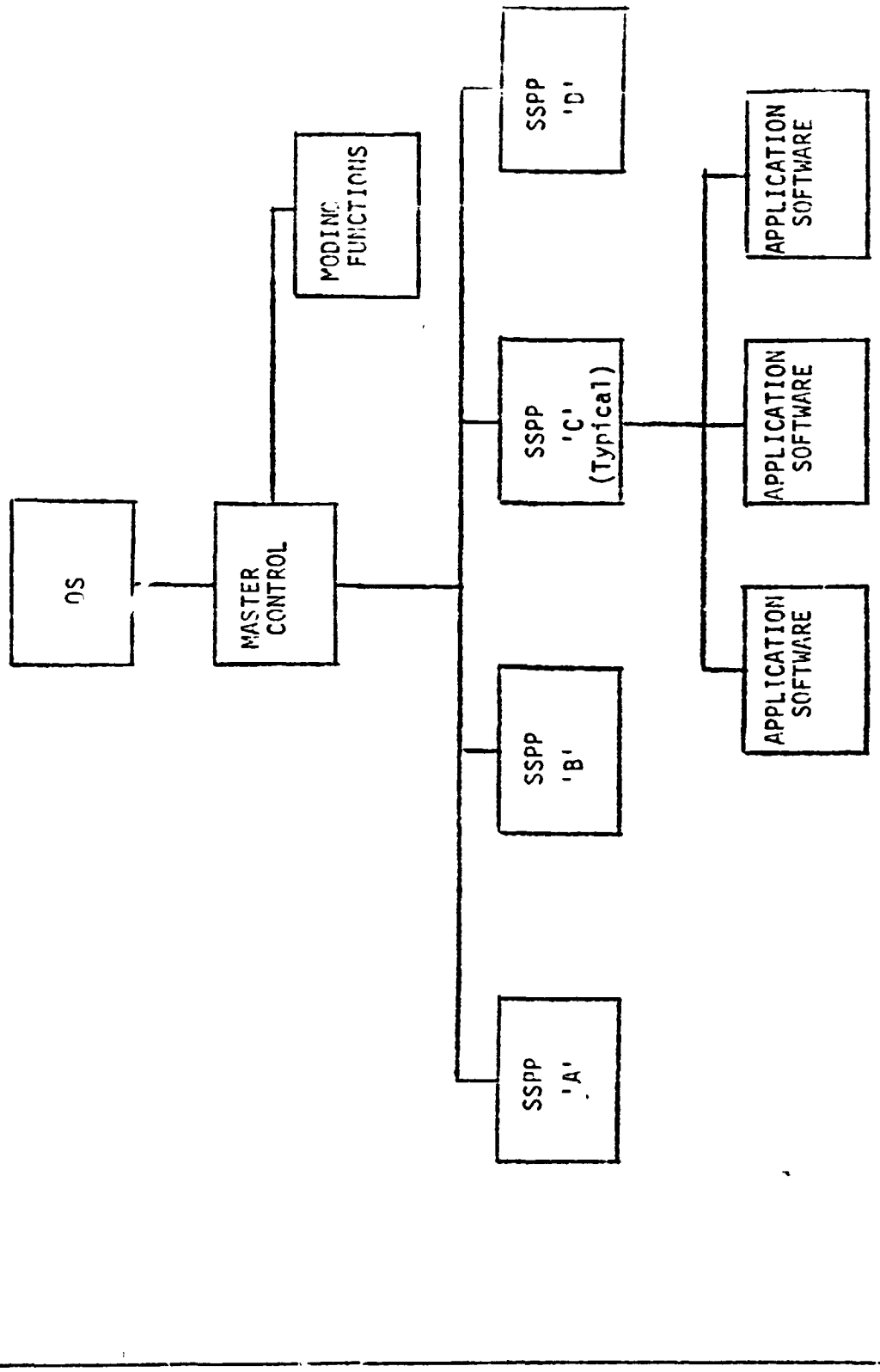


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FIGURE 4.4.1.9.2-1
CONTROL STRUCTURE

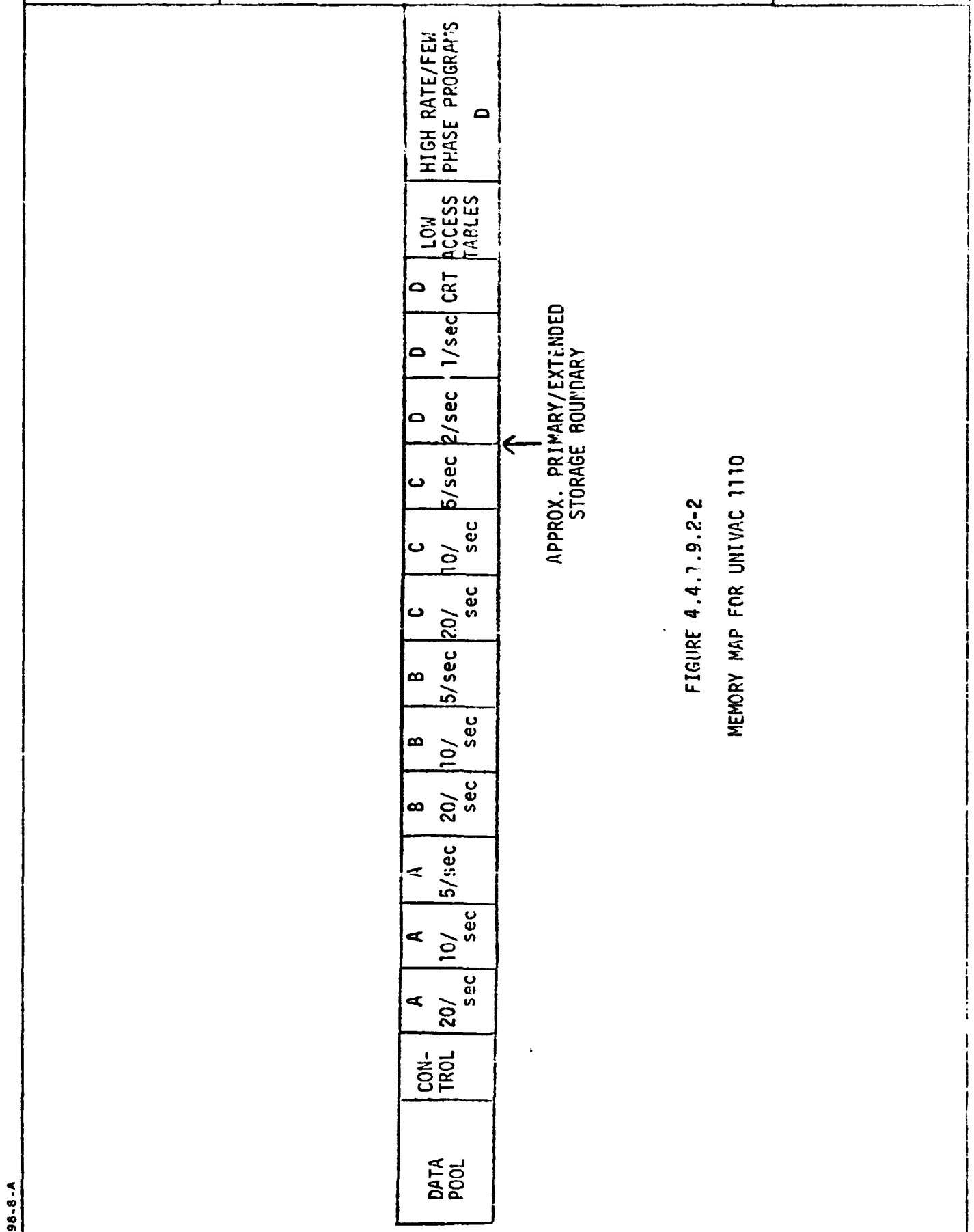

FIGURE 4.4.1.9.2-2

MEMORY MAP FOR UNIVAC 1110

F-398-8-A

4.4.1.9.3 Simulation Software Structure in Xerox Sigma 9

The Xerox Sigma 9 complex contains two configurations: Four Sigma 9's with 448K words of memory, and five Sigma 9's with 512K words of memory.

4.4.1.9.3.1 General Requirements

The following requirements were made during the structure definition:

4.4.1.9.3.1.1 CPU Execution Rate

That each Sigma 9 is capable of executing 0.8 million instructions per second.

4.4.1.9.3.1.2 Memory Available to Each CPU

That all CPU's are capable of accessing all core memory within the configuration.

4.4.1.9.3.1.3 Memory Available to I/O System

That a part of the I/O system, under control of one CPU, can access all core memory within one configuration.

4.4.1.9.3.1.4 Background Processing

That the configuration has no requirement for background processing concurrent with simulation.

4.4.1.9.3.1.5 Operating System

That the simulation software structure will execute under direct control of a standard vendor-supplied real-time operating system (e.g., CP-V). That the operating system is cognizant of the fact that there are multiple CPU's in the configuration.

4.4.1.9.3.1.6 External Interrupts

That upon the occurrence of an external interrupt, the operating system will pass control to a unique point in the simulation package.

4.4.1.9.3.1.7 Paralle ism

That large portions of the simulation software can be executed in parallel.

4.4.1.9.3.1.8 Serial Execution

When the simulation software must be executed in a serial mode, that software will be executed in one, and only one, CPU. The computational demand does not exceed the limit of 4.4.1.9.3.1.1 above.

4.4.1.9.3.2 Simulation Software Structure

4.4.1.9.3.2.1 Basic Structure

The basic structure for the five CPU configuration is shown in Figure 4.4.1.9.3.-1. It will be obvious that the same structure can be used in the four CPU configuration. A core memory map is shown in Figure 4.4.1.9.3-2

As can be seen, this approach has no overlay segments. The basic rationale for this decision is as follows:

Due to the number of CPU's, the size of any particular overlay segment would not justify the number of high-speed mass storage devices that would have to be dedicated to each CPU.

4.4.1.9.3.2.2 Jump List Management

The simulation software will be organized into five separate jump lists: A, B, C, D, and E. The occurrence of a program call in any particular jump list will be a function of four constraints:

- The effect of parallelism upon the module.
- The requirement for serial execution.
- Program iteration rate.
- Mission phases for which execution is required.

It is anticipated that the total execution demands will be spread evenly across all CPU's.

Inspection of the memory map shows that, where possible, the program load for each CPU will be contained in separate areas of memory. This will confine most memory conflict to the data pool and subroutine areas.

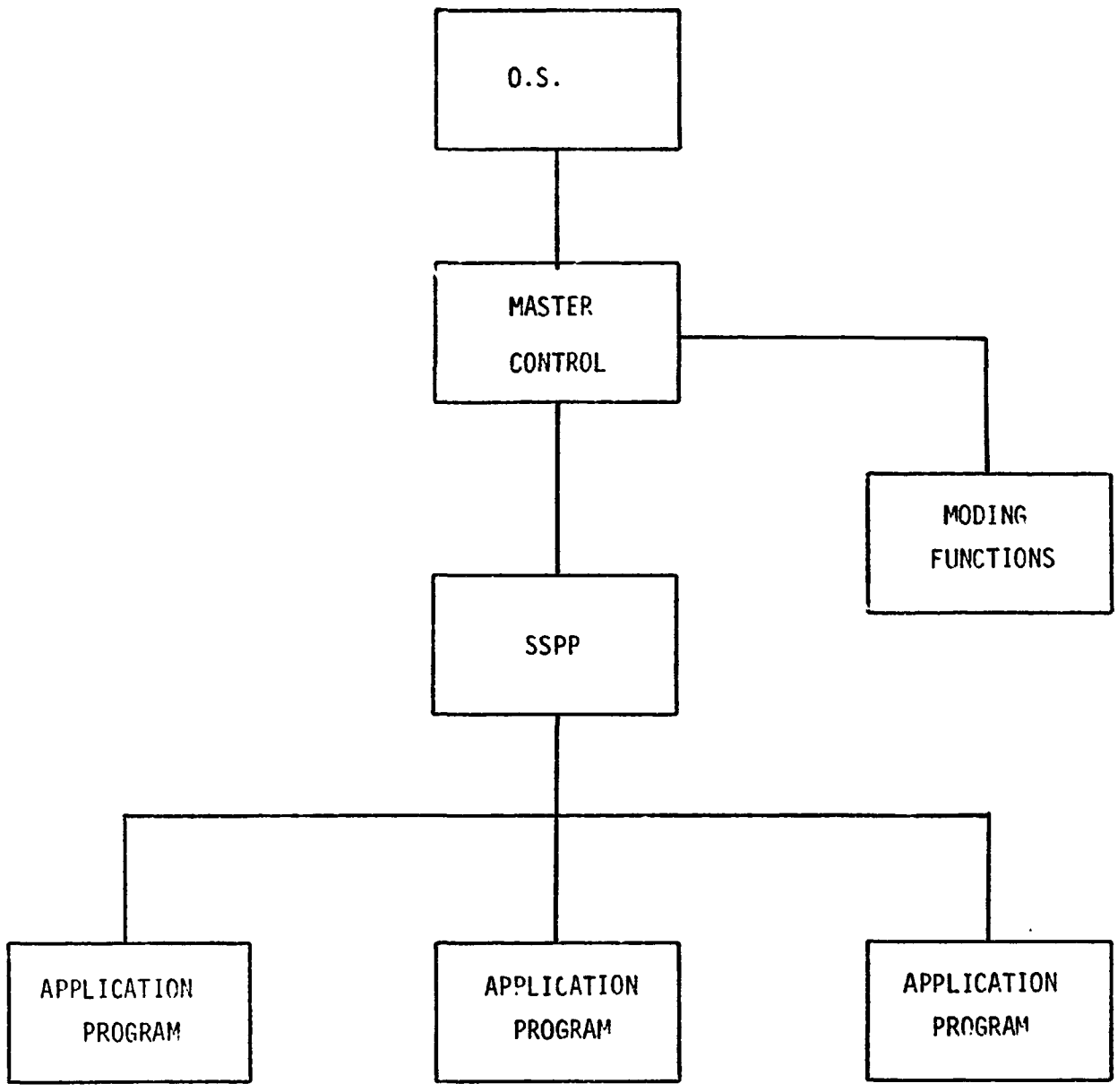

FIGURE 4.4.1.9.3-1

XDS Typical Software Structure (One CPU)

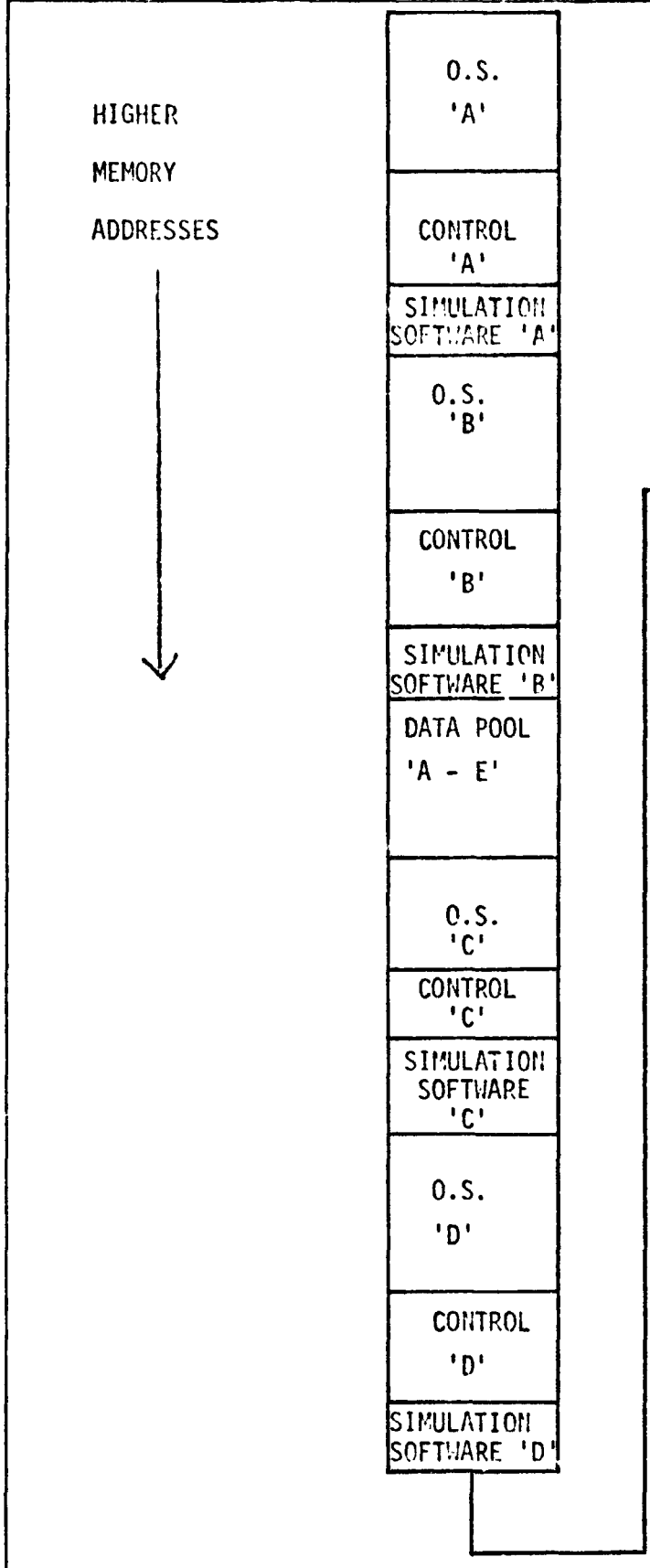

FIGURE 4.4.1.9.3-2

XDS Core Memory Map

3.4.1.9.4 Simulation Software Structure in the IBM Configuration

The IBM complex contains one MP168 with 4 1 bytes shared memory.

4.4.1.9.4.1 General Requirements

The following requirements were made which apply directly to the structure definition:

4.4.1.9.4.1.1 CPU Execution Rate

Each CPU is capable of executino at least 4.0 million instructions per second.

4.4.1.9.4.1.2 Program/CPU Dependency

That a direct relationship can exist between a particular program and a particular CPU.

4.4.1.9.4.1.3 Operating System

That the operating system will be VS/2.2 or an upward compatible system.

4.4.1.9.4.1.4 Parallelism

Large portions of the simulation software can be executed in parallel.

4.4.1.9.4.1.5 Serial Execution

When the simulation software must be executed in a serial mode, that software will be executed in one, and only one, CPU. The computational demand does not exceed the limit of 4.4.1.9.4.1.1 above.

4.4.1.9.4.1.6 External Interrupts

Upon the occurrance of an external interrupt, the operating system will pass control to one unique entry point in the simulation software package.

4.4.1.9.4.2 Structure

4.4.1.9.4.2.1 Basic Structure

The structure does not utilize overlay segments. The rationale for this is as follows:

- To implement a simple overlay structure will require dedicated use of one or more high speed drum memories per complex.

The structure is illustrated in Figure 4.4.1.9.4-1. A core memory map is shown in Figure 4.4.1.9.4-2. This structure will be utilized by both MBCS and FBCS simulation loads.

The figure illustrates that all simulator control functions are performed in the "A" computer. The 'sync control' module inhibits SSPP execution until notified by master control that parallel execution may proceed. After the "B" SSPP has completed execution of a frame, the sync control module causes the simulation programs in the "B" computer to re-enter the wait state until again posted by master control.

4.4.1.9.4.2.2 Jump List Management

The simulation software will be organized into two separate jump lists, A and B. The occurrance of a program call in either jump list will be a function of four constraints:

- The effect of parallelism upon the module.
- The requirements for serial execution.

- Program iteration rates.
- Mission phases for which execution is required.

The "B" jump list will exist as a daughter task to the "A" jump list, eliminating memory protect conflicts. The two jump lists will be kept in sync via a "WAIT/POST" arrangement.

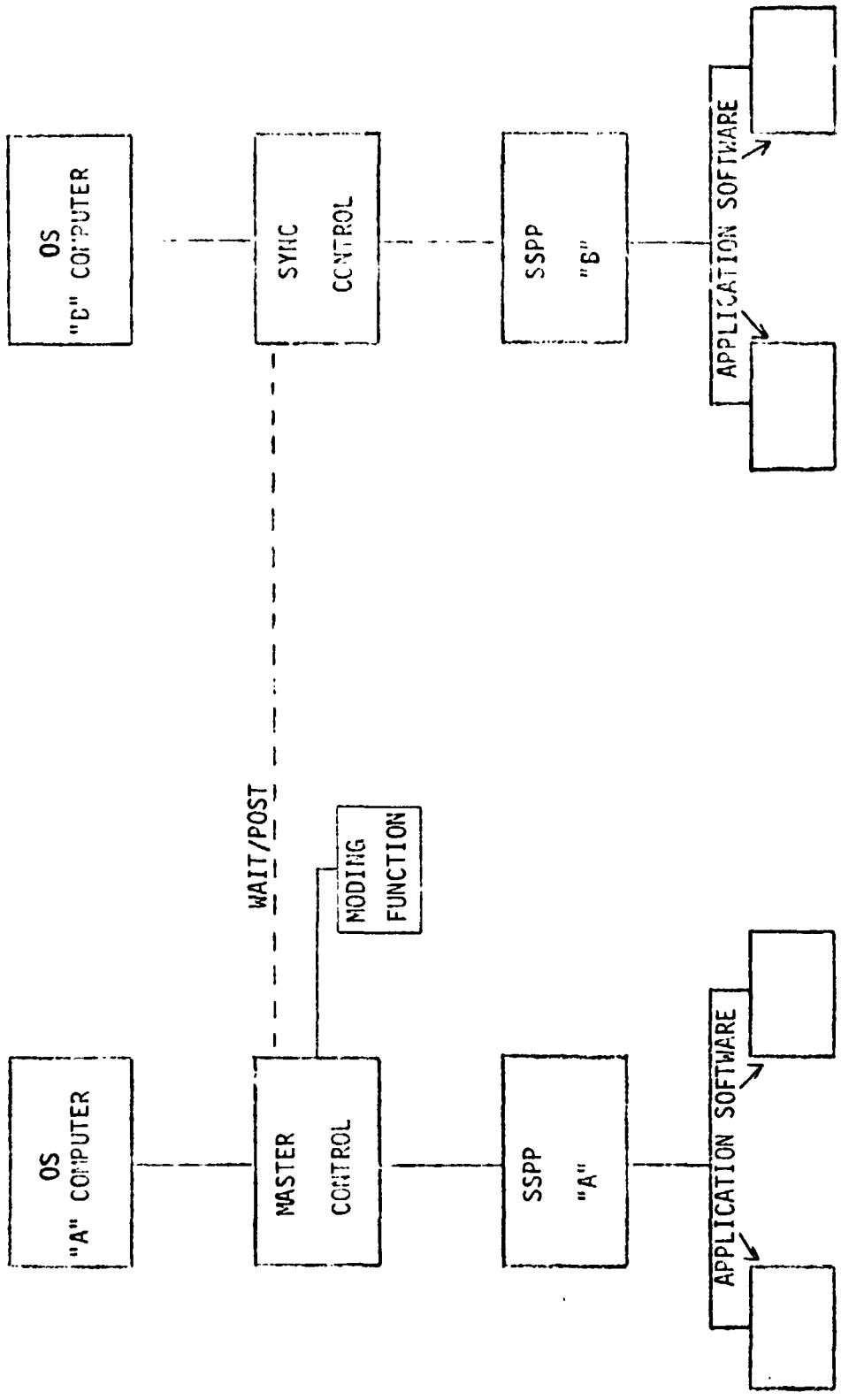

FIGURE 4.4.1.9.4-1
IBM STRUCTURE

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DATA POOL	CONTROL SOFT-WARE	20/Sec "A"	10/Sec "A"	5/Sec "A"	2/sec "A"	1/sec "A"	20/Sec "B"	10/Sec "B"	5/Sec "B"	2/sec "B"	1/sec "B"

FIGURE 4.4.1.9.4-2

IBM STRUCTURE MEMORY MAP

DATE 6/23/73
REV.
THE SINGER COMPANY
SIMULATION PRODUCTS DIVISION
BINGHAMTON, NEW YORK
PAGE NO. 4.4-43
REP. NO.

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4.4.1.9.5 Simulation Software Structure in the Control Data Configuration

The Control Data Configuration consists of one 7600 CPU, 65K words SCM, 512K words LCM.

4.4.1.9.5.1 General Requirements

The following requirements were made which apply directly to the structure definition:

4.4.1.9.5.1.1 CPU Execution Rate

The 7600 CPU is capable of executing 15.0 million instructions per second. This rate will be degraded to 12.0 million instructions per second by block transfers to/from SCM/LCM.

4.4.1.9.5.1.2 Operating System

The operating system will be Scope 2, or an upward compatible system.

4.4.1.9.5.1.3 External Interrupts

Upon the occurrance of an external interrupt, the operating system will pass control to one unique entry point in the simulation software package.

4.4.1.9.5.1.4 Operating System Size

The operating system will require the first 8K of SCM, and the first 65K of LCM.

4.4.1.9.5.2 Structure

4.4.1.9.5.2.1 Basic Structure

The basic software structure consists of multiple overlay segments rolled into SCM from LCM, using the block transfer instruction. The software structure presented in this section is applicable to either crew

station; hence the structure defined will be for Crew Station "X". A duplicate structure will be required for Crew Station "Y".

A core memory map is shown in Figure 4.4.1.9.5-1. As can be seen from the figure, the programs are grouped in one area of LCM; the "program commons" (data needed by only one program) are in another area; and the "global common" (data needed by two or more programs) is in a third area. (A program, P1, has program common C1; Program P2 has program common C2, etc. Program P2 does not need any data from any "C" except C2).

4.4.1.9.5.2.1.1 SCM Utilization

The simulation software will view SCM as if it has the format depicted in Figure 4.4.1.9.5-2.

Due to the computer architecture, the CPU executes at its fastest rate when both programs and data reside in SCM. It is the function of the "jump list sequencer and memory management" (JSMM) routine to move programs and their common areas into SCM, execute the program, then move the program common back to LCM until needed again by the program.

4.4.1.9.5.2.1.2 LCM Utilization

LCM is used as a high-speed mass storage device. As noted above, the simulation programs, program common and global common reside in LCM and are rolled in from LCM to SCM prior to execution. After the program has executed, its program common is rolled back out to LCM. When all programs in a frame have executed, the global common is rolled out to LCM.

4.4.1.9.5.2.1.3 Typical Frame Execution

For illustrative purposes, let us assume that a computational frame contains two programs, "P1" and "P2", which have program commons "C1" and "C2", the global common used is "GC".

The following events will occur during the frame execution:

- Occurrance of an external interrupt (e.g., 50 ms pulse) will cause the operating system to load SCM with the JSMM.
- The JSMM will move global common "GC" into SCM.
- JSMM will move program common "C1" into the program common area of SCM.
- JSMM will move program "P1" to the program area of SCM.
- JSMM causes program "P1" to be executed.
- At the conclusion of Program "P1" execution, the JSMM will move program common "C1" back to where it existed in LCM, and will move program common "C2" into the program common area of SCM.
- JSMM will move program "P2" into the program area of SCM.
- JSMM causes program "P2" to be executed.
- At the conclusion of Program "P2" execution, the JSMM will move program common "C2" back to where it existed in LCM.
- The JSMM senses the end of the frame and moves the global common 'GC" back to where it existed in LCM.
- Its work completed for this frame, JSMM returns to the operating system until the next external interrupt.

4,4.1.9.5.2.1.4 Two Crew Station Operation

Since both crew stations will have the same basic structure, the principal difference between them is the external interrupt used to begin execution. It is envisioned that the central timing equipment will supply two 20 per second pulses spaced 25 milliseconds apart. Thus each crew station receives a 50 ms pulse for internal framing.

It may prove desirable to supply a "1 pulse per second" and "1 pulse per minute" for each crew station, the two pulses of each type separated by 25 milliseconds. This will allow correct synchronization when integrated with MCC or another complex.

4.4.1.9.5.2.2 Jump List Management

All of the simulation programs will be executed from one jump list, which is made up of 20 frames. The occurrance of a program call in the jump list will be a function of two constraints:

- The requirement for serial program execution.
- Program iteration rate

Each entry in the jump list will consist of five elements:

- Program address in LCM
- Program length
- Program common address in LCM
- Program common length
- Flags indicating for which mission phases the program is to execute.

The JSMM routine will check the mission phase flags prior to moving the program or its common, eliminating the movement overhead if the module is not being executed.

The first and last entry in the jump list will contain flags to the JSMM indicating the LCM location and length of the global common area.

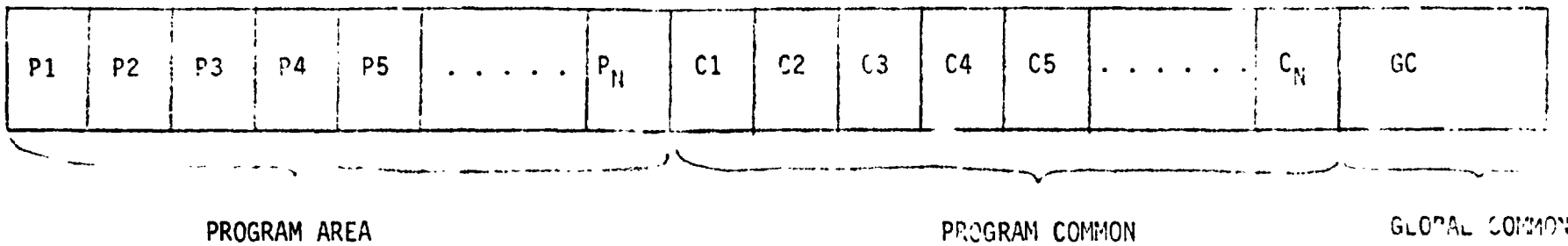

FIGURE 4.4.1.9.5-1

CDC LCM MEMORY MAP OF SIMULATION SOFTWARE

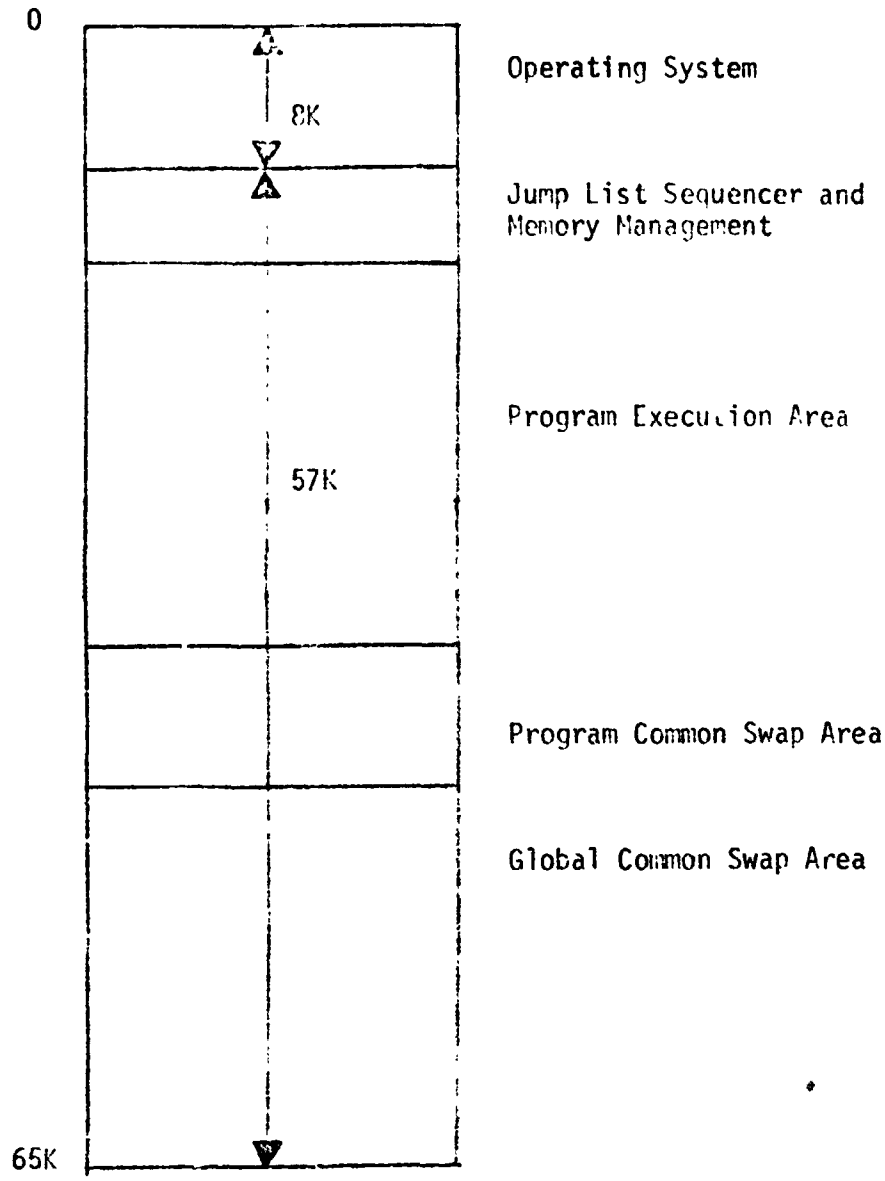

FIGURE 4.4.1.9.5-2
SCM LAYOUT

4.4.2 Data Management System (DMS)

The DMS as depicted in Figure 4.4.2-1 will provide the maintenance and status capabilities, through an automated process, of the detailed hardware and software configuration of the SMS.

The focal point of the DMS is the Generalized Data Base Management System (GDBMS). The GDBMS is a computer manufacturer's system (CODASYL Standard) data base management system. The GDBMS should provide the following major features:

Data Structure

Data structure is the view of the data as seen by the user of the system and excluding any details of storage techniques used which are covered in a separate section. An understanding of the data structure of either kind of data base system is essential to a good understanding of its capabilities.

Data structure levels are identified as item, group, group relation, entry (record), file and data base. The definition of a data structure is referred to throughout the report as a schema. It is also possible in some systems to have several sub-schemas which are subsets of the schema.

Data Definition

The language and/or tabular formats used to define a schema representable within the system's capability to handle data structures.

Interrogation

Interrogating a data base is a process of selecting and extracting some part of the whole data base for display, usually in a hard copy printed form. One section of the interrogation function defines how the part is selected. The second part covers how operations such as computation, sorting and formatting may be performed on the selected part. The concept of interrogation is an

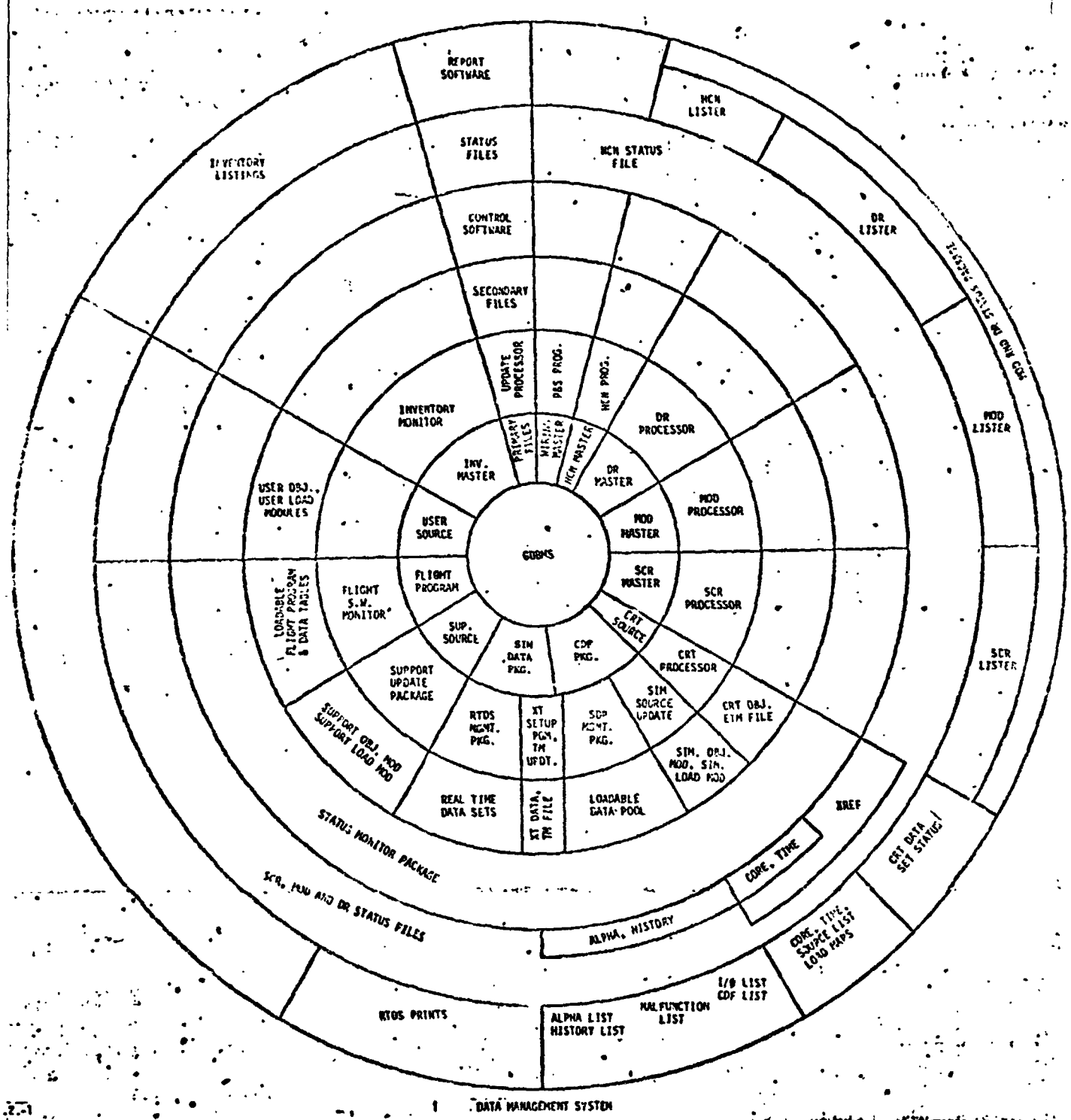

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Figure 4.4.2-1

intrinsic self-contained capability. The implication is that the user is able to formulate a query in the language of the system without detailing the sequence of steps used to access the data base and extract the information.

Availability of the interrogation function implies that a built-in processing algorithm for the function is provided by the system. In the simplest case, the processing algorithm is that of sequentially searching a stored file, copying out records which satisfy some conditional expression, and building up a report based on the data contained in these records. There are many degrees of sophistication even within the framework of the basic sequential search algorithm. Other processing algorithms cause the file to be accessed to obtain the required inforation, using various techniques which avoid a sequential search.

Update

Updating a data base is a process of changing the value content of some part of the data base. It excludes restructuring of the data which would cause a modification to the stored data definition. Update is a process somewhat analogous to interrogation in that some part of the data base must first be selected. In most self-contained systems, the selection facilities are modelled on those used in the interrogation function. However, once the part is selected, it is changed in some defined way rather than displayed in a report.

Update is intrinsically a self-contained capability. It also implies a built-in processing algorithm, but the possible ways of implementing it are even more varied than for interrogation. In some systems, both update and interrogation can be performed during the same sequential pass of a file in the data base.

Creation

An important preliminary to the creation function is that of data definition. It is necessary to provide a set of records to form the initial instance of a file. Other functions are data validation, security specification and control over media type. Data base creation is considered to be one of the important functions for the data administrator. Creation may imply a built-in processing algorithm as for interrogation and update, or it may have to be programmed in a conventional sense. In many cases it is a use of the updating function applied to a null file.

There is no clear division here between self-contained systems and host language systems. Some self-contained systems do require a programmed approach to file creation. This implies that providing the initial instance of the file is a function which has to be programmed using facilities other than those provided by the system.

Programmer Functions

Programmer functions are defined as host language capabilities. They are functions upon which a programming user may call when writing a program in a host language. The most important programmer function statements are those which permit him to initiate data transfers between the stored data base and high speed memory. Other statements may be provided to allow him to issue file control statements such as open, close and hold.

Any function considered to be in the domain of the data administrator, even though its use may be on the level of the programmer, is not considered in this section.

Data Administrator Functions

The data administrator is an individual responsible for a data base. His role is identified to some extent in both host language and self-contained systems. Such functions include monitoring system operation, preservation of system integrity and security, and providing for restructuring the data base to accommodate new record types or new items. Some of the data administrator's functions may have to be performed with a programmer level language in some systems. In this case the designation of a function as an administrator function is subjective.

Storage Structure

Each level of the data structure has a stored representation which is referred to as the storage structure. The file level storage structure defines how entries are stored in physical blocks to form the stored representation of the file. This level is often dictated by the input/output control system, which in third generation operating systems has been given the name of data management system. File level storage structures include such techniques as indexed sequential and other ways of storing a file and data about it to facilitate access to its contents.

The entry level storage structure varies more widely among systems and it defines how groups or items are represented in storage to form the stored representation of an entry. Sometimes all entry data is stored contiguously in low speed memory, but in some systems groups are mapped into segments wher the segments in an entry may be stored in different locations in low speed memory. Finally item level storage structure usually reflects the storage modes of the machine although systems exercise different levels of control in their data structure over the mapping of items into storage structure formats.

The following paragraphs describe the functions and capabilities that the Data Management System of the SMS should provide:

4.4.2.1 Simulation Source Management System

4.4.2.1.1 Master Domain

4.4.2.1.1.1 Files

CRT Source Modules - A library will be maintained containing one member for every CRT source program in compressed form. This library would contain test areas for testing new page programs as they are being developed.

Simulator Software Source - A library will be maintained containing one member for every operational program in compressed source form. Strict coding conventions will be applied to insure the utilization of the self documenting features of a source language to its fullest extent.

4.4.2.1.1.2 Processors

CRT Off-Line Processor - A processor will be provided to update CRT source programs and compile them into an object library accessible by the real-time CRT processor. Event time monitor information will also be provided to the CRT on-line processor through this program. Additional information will be passed to the Status Monitor Package and the cross reference data set will be modified for every CRT page which undergoes a permanent source update. Source listings which result will be passed to a simulator source listing data set.

Simulator Source Update Processor - The fa : ties will be available to make program changes both permanent and temporary to operational programs. Object data sets will result which will later be meshed with other routines through a load generation process. Source listings which result will be passed to a Simulator Source Listing data set.

4.4.2.1.2 Control Domain

4.4.2.1.2.1 Files

CRT Object Program Library - A library will be maintained providing one member for each CRT page in operational or test status. This library will

be of a direct access nature to permit fast access by the CRT on-line processor.

ETM File - This file will provide the real-time CRT processor with the information needed to generate the event time monitor and tripped circuit breaker displays. This file will be of a direct access nature to permit fast access by the CRT real-time processor.

Simulator Software Object - An object library which will maintain at least one object copy of every operational program. The modules will be accessed from this library by the program which builds loadable modules.

Simulator Source Listings - Source listings for all simulator software will be maintained in compressed form that they may be called out for listing at any time from a remote site or the central processor station.

4.4.2.1.2.2 Processors

Core Loading Monitor Program - A program will be provided to analyze the output of the loader program and give edited printouts, including module lengths in decimal and other special data pertinent to the task structure.

Status Monitor Package - A group of programs will be provided to update, according to the type of update, the SCR, Mod, and DR status file. Programs in this package will be called directly from processors in the Master Domain.

Time Loading Monitor Program - The time loading monitor program will be a special real-time executive which will extract timing information from individual routines as they run and store this information in the Time Loading Status File for future reference.

4.4.2.1.3 Report Domain

4.4.2.1.3.1 Files

Core Loading Status File - A file will be maintained which contains all core loading information as provided by the Core Loading Monitor Program.

This data will consist of program names, size, and overlay segment if applicable.

Cross Reference (XREF) Data Set - A data set containing one member for each source module and each CRT source program will exist denoting all SDP terms used by that program in its current status. This information is provided by the Simulator Source Update Package and the CRT off-line processor.

SCR, Mod, and DR Status File - A file will be maintained to describe all SCR's, Mods and DR's as to their status and effect on simulation. Information from this file will be unloaded to permanent storage when a given time period has elapsed after final incorporation into a training simulator load.

Time Loading Status File - A file will be kept current containing timing information on every simulator software module.

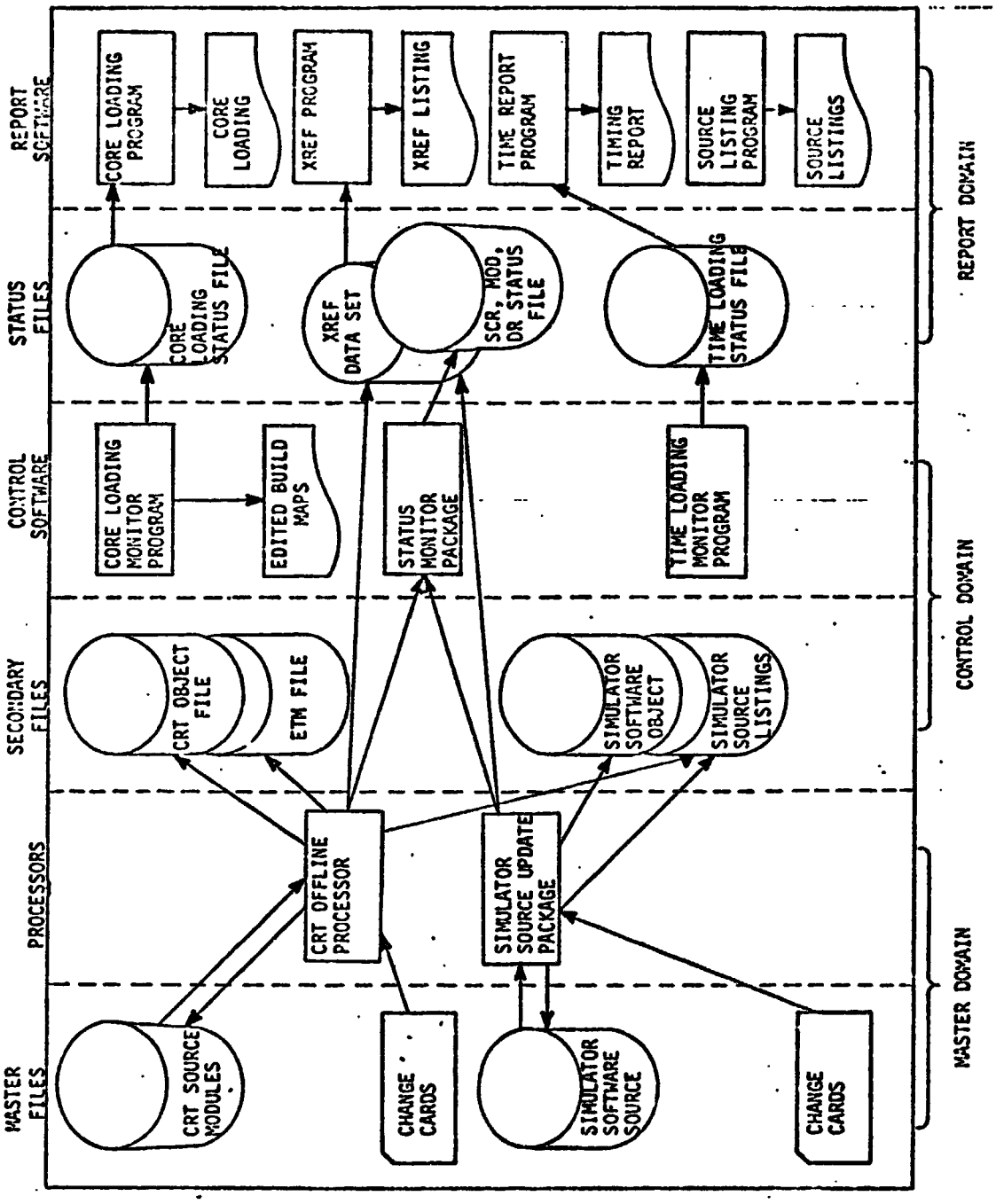
4.4.2.1.3.2 Processors

Core Loading Program - A program will be developed to provide complete core utilization reports from the Core Loading Status File.

XREF Program - A program will be maintained to provide a cross reference of all terms used in the simulator source by term and by program. An additional facility will provide a printout of all terms not used but maintained in the SDP.

Time Report Program - A method will be provided for generating automated time reports from information contained in the Time Loading Status File.

Source Listing Program - A program will be maintained to selectively print source listings from the Simulator Source Listing File with options for printing or suppressing assembly language printouts, cross references, maps, etc.



4.4.2.1 Simulation Source Management System

4.4.2.2 Simulation Data Pool Management System

4.4.2.2.1 Master Domain

4.4.2.2.1.1 Files

Configuration Data File - Sufficient information will be contained in the Configuration Data File to describe completely every term referenced by the real-time simulation source modules. This information will include, but not limited to, description, range or value, units, scaling (fixed point), array information, data type and precision.

Simulator Software Source - A library will be maintained containing one member for every operational program in compressed source form. Strict coding conventions will be applied to insure the utilization of the self documenting features of a source language to its fullest extent.

4.4.2.2.1.2 Processors

Simulation Data Pool Management Package - Processors will be developed to generate, from the configuration data file and change cards, updated History and Alpha files. In addition, a processor will be developed to generate the necessary data pools in the form of source modules, which will be added to the Simulator Software Source File. Appropriate information will be passed to the Status Monitor Package to provide a history of all changes made.

4.4.2.2.2 Control Domain

4.4.2.2.2.1 Files

Alpha File - Configuration Data File items pertaining to each data pool term are contained in the Alpha file. This data will be sufficient to provide linkage to the data pool for source programs. The term records are in alphabetical order.

4.4.2.2.2.2 Processors

Status Monitor Package - A group of programs will be provided to update, according to the type of update, the SCR, Mod, and DR status file. Programs in this package will be called directly from processors in the Master Domain.

4.4.2.2.3 Report Domain

4.4.2.2.3.1 Files

History File - The History file will contain comparable information to the Alpha file however it will be arranged in core order rather than alphabetical order. Each location in each data block will be accounted for.

SCR, Mod and DR Status File - A file will be maintained to describe all SCR's, Mods and DR's as to their status and effect on simulation. Information from this file will be unloaded to permanent storage when a given time period has elapsed after final incorporation into a training simulator load.

4.4.2.2.3.2 Processors

SDP Report Generation Software - Sufficient software will be developed to generate reports including, but not limited to, the following:

Malfunction Lists

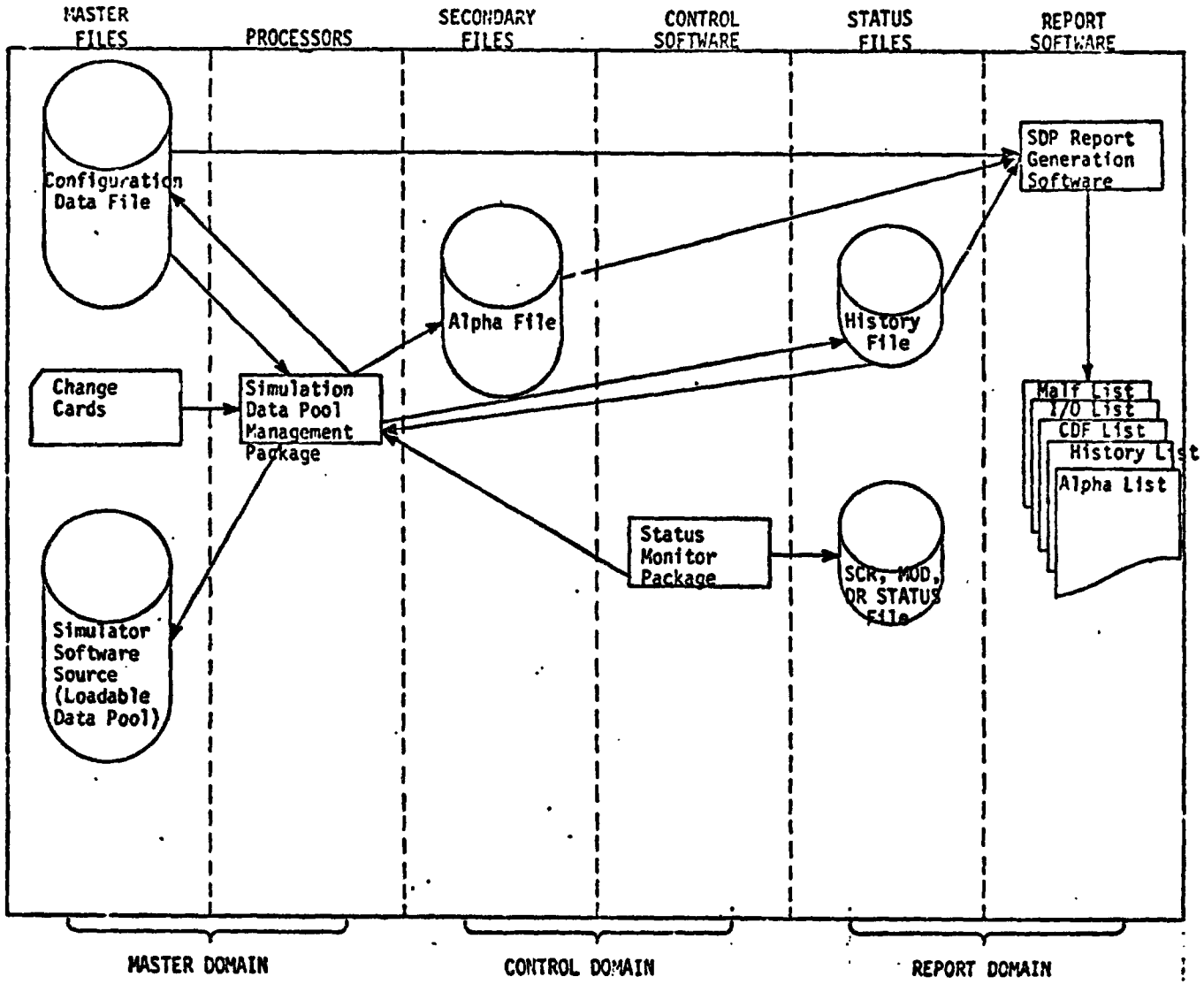
I/O Term Lists

CDF List

History List

Alpha List

4.4.2.2 Simulation Data Pool Management System



4.4.2.3 Simulation Data Package Management System

4.4.2.3.1 Master Domain

4.4.2.3.1.1 Files

Simulation Data Package - The simulation data package contains all data received from outside sources. This data will be used for, but not limited to, creating the following real-time data sets:

Reset

Flight Computer Resets

Aero Tables

Ephemeris Data

Visual Data (Film Constants)

4.4.2.3.1.2 Processors

Simulation Data Processor Package - A separate processor program will be developed for generating each real-time data set to be derived from the Simulator Data Package. Status information will be passed to the Status Monitor Package. Update capability will be provided to change any data in the package as new data is received.

4.4.2.3.2 Control Domain

4.4.2.3.2.1 Files

Real-Time Access Data Files - The extent to which real-time data sets will be provided will be determined by the requirements of the simulator task.

4.4.2.3.2.2 Processors

Status Monitor Package - A group of programs will be provided to update, according to the type of update, the SCR, Mod, and DR status file. Programs in this package will be called directly from processors in the Master Domain.

4.4.2.3.3 Report Domain

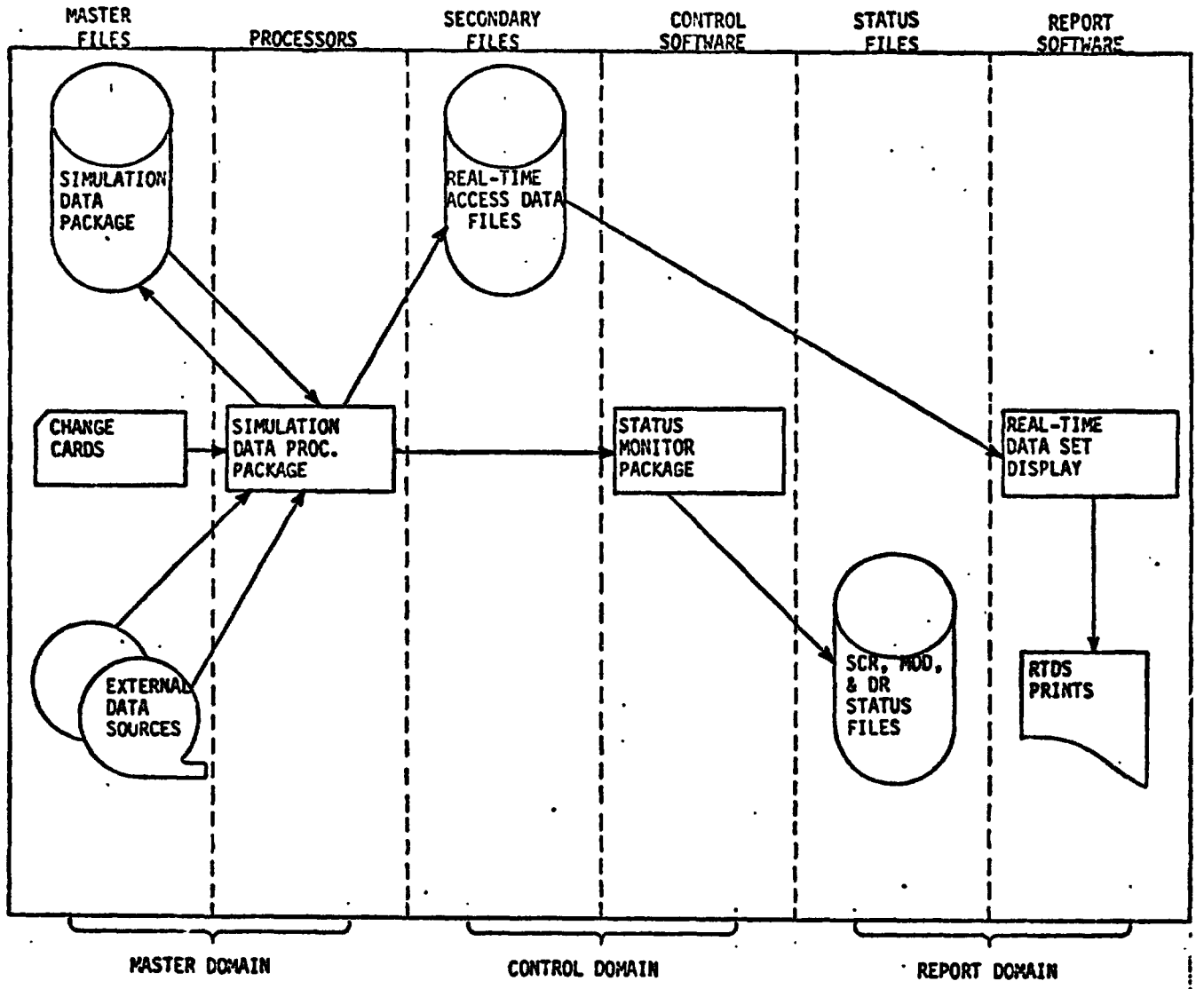
4.4.2.3.3.1 Files

SCR, Mod and DR Status Files - A file will be maintained to describe all SCR's, Mods and DR's as to their status and effect on simulation. Information from this file will be unloaded to permanent storage when a given time period has elapsed after final incorporation into a training simulator load.

4.4.2.3.3.2 Processors

Real-Time Data Set Display Package - Sufficient display programs will be developed for formatting printouts of all real-time data sets.

4.4.2.3 Simulation Data Package Management System



4.4.2.4 Support Software Management System

4.4.2.4.1 Master Domain

4.4.2.4.1.1 Files

Support Software Master Source - All utility support source not pertaining to Sections 4.4.2.1, 4.4.2.2 or 4.4.2.3 will be contained in Support Software Master Source Library. Software in this library is controlled source, changeable through standard SCR procedures.

4.4.2.4.1.2 Processors

Support Source Update Processor - The capability will exist within the support source update processor to update existing source, create appropriate object modules and communicate appropriate information to the Status Monitor Package.

4.4.2.4.2 Control Domain

4.4.2.4.2.1 Files

Support Software Load Modules - All support software will be kept in a load module library ready for execution with no pre-processing required.

Support Software Modules - Individual subroutines may be placed in an object module library for later incorporation into a load module when combined with other subroutines.

4.4.2.4.2.2 Processors

Status Monitor Package - A group of programs will be provided to update, according to the type of update, the SCR, Mod, and DR status file. Programs in this package will be called direct from processors in the Master Domain.

4.4.2.4.3 Report Domain

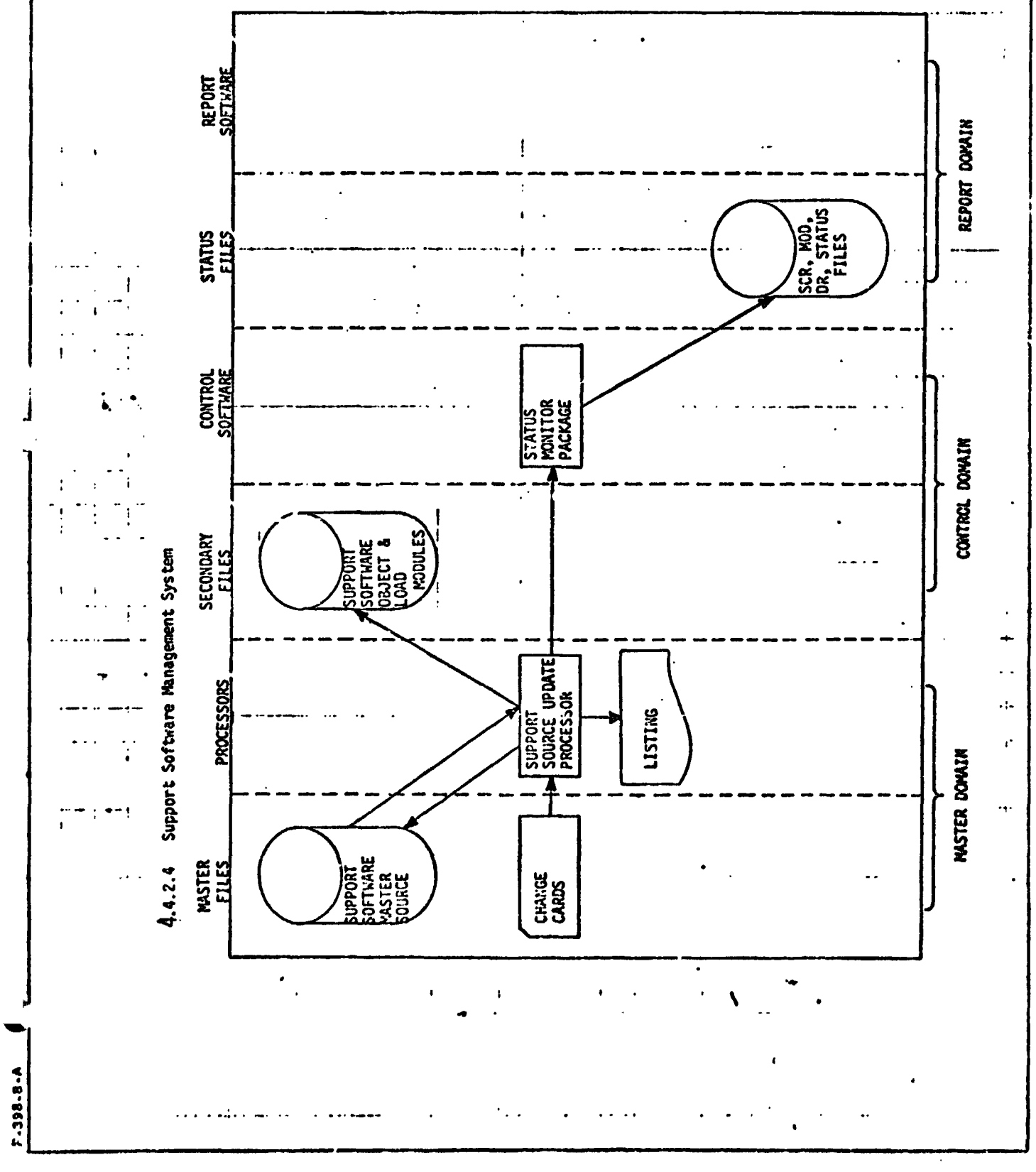
4.4.2.4.3.1 Files

SCR, Mod and DR Status Files - A file will be maintained to describe all SCR's, Mods and DR's as to their status and effect on simulation. Information

from this file will be unloaded to permanent storage when a given time period has elapsed after final incorporation into a training simulator load.

4.4.2.4.3.2 Processors

Not applicable.



4.4.2.4 Support Software Management System

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4.4.2.5 Flight Program Management System

4.4.2.5.1 Master Domain

4.4.2.5.1.1 Files

Flight Program Master Source - Flight Program masters are to be kept in a library which contains one program per member. Any additional flight program source information, such as data tables, will be kept in the same data set as members.

4.4.2.5.1.2 Processors

Flight Program Update Processor - A program will be provided to make updates to the stored flight program sources, produce loadable flight programs and any other flight information required for real-time operation exclusive of reset, which will be handled elsewhere. Information will be passed directly to the Status Monitor Package describing the changes made to the flight source.

4.4.2.5.2 Control Domain

4.4.2.5.2.1 Files

Loadable Flight Program - Flight programs will be stored in a library accessible to on-line operation on a read only basis.

Real-Time Flight Program Data Sets - Data sets which are necessary for real-time flight program operations will be provided. This does not include reset data, which is part of the Real-Time Data Set Package.

4.4.2.5.2.2 Processors

Status Monitor Package - A group of programs will be provided to update, according to the type of update, the SCR, Mod and DR status file. Programs in this package will be called directly from processors in the Master Domain.

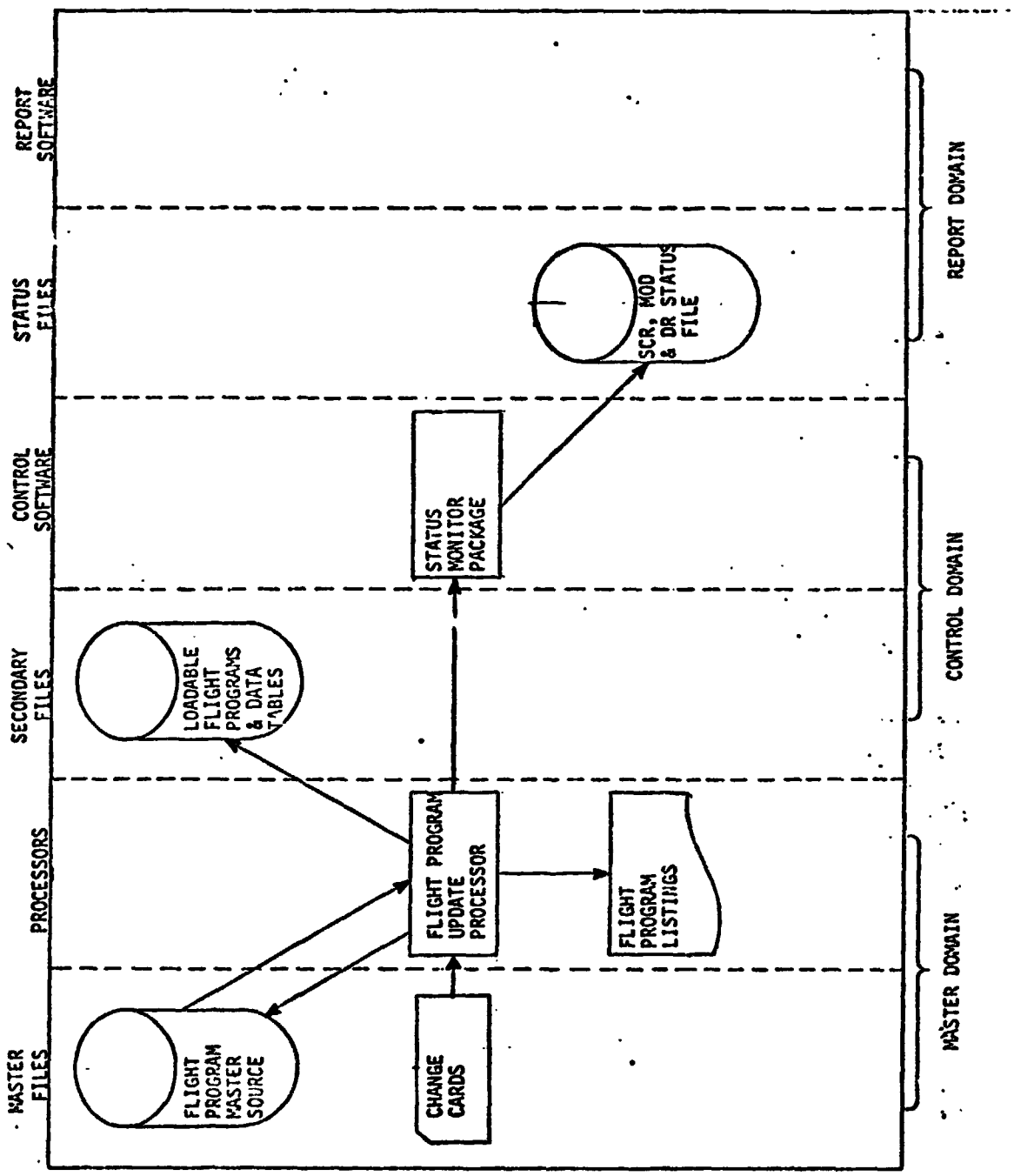
4.4.2.5.3 Report Domain

4.4.2.5.3.1 Files

SCR, Mod, and DR Status Files - A file will be maintained to describe all SCR's, Mods and DR's as to their status and effect on simulation. Information from this file will be unloaded to permanent storage when a given time period has elapsed after final incorporation into a training simulator load.

4.4.2.5.3.2 Processors

Not Applicable



4.4.2.5 Flight Program Management System

4.4.2.6 Supply Inventory

The Supply Inventory System is a computer based system which will control the supply inventory, providing up to-date reports with a minimum amount of delay.

4.4.2.6.1 Master Domain

4.4.2.6.1.1 Master Files

The two master files associated with the supply inventory are the Supply Inventory Master and the Transaction Master. The Supply Inventory Master file will contain the basic information on the items in the inventory such as: manufacturer part number, control number, part name, description, stockroom location, minimum stock level, maximum stock level, quantity on hand, unit cost, and if the item is available from Federal Stock.

The Transaction Master will contain all the transactions occurring against the inventory. The information will contain such information as: control number, type of transaction, quantity, disposition and total cost of transaction.

4.4.2.6.1.2 Processors

Two types of data are input the Supply Inventory Processor (SIP): basic inventory data designating stock items which comprise the inventory base, and quantity change data (transactions), which will include item issue records, receipts, re-order confirmations, and stock returns. This data would be input via CRT's or card.

The SIP will process the inputs against the Supply Inventory Master and Transaction Master files and will generate the re-order and excess reports.

Once the quantity-on-hand of an item drops below the stated minimum, it is put on the re-order report. Since some items are available from Federal Stock while others are not, one of two actions will be performed. For all items available from Federal Stock, the re-order form will be printed and a re-order transaction will be generated. For all items not available from federal stock, the re-order and re-order transaction must be generated manually.

4.4.2.6.2 Control Domain

4.4.2.6.2.1 Secondary Files

None

4.4.2.6.2.2 Control Software

None

4.4.2.6.3 Report Domain

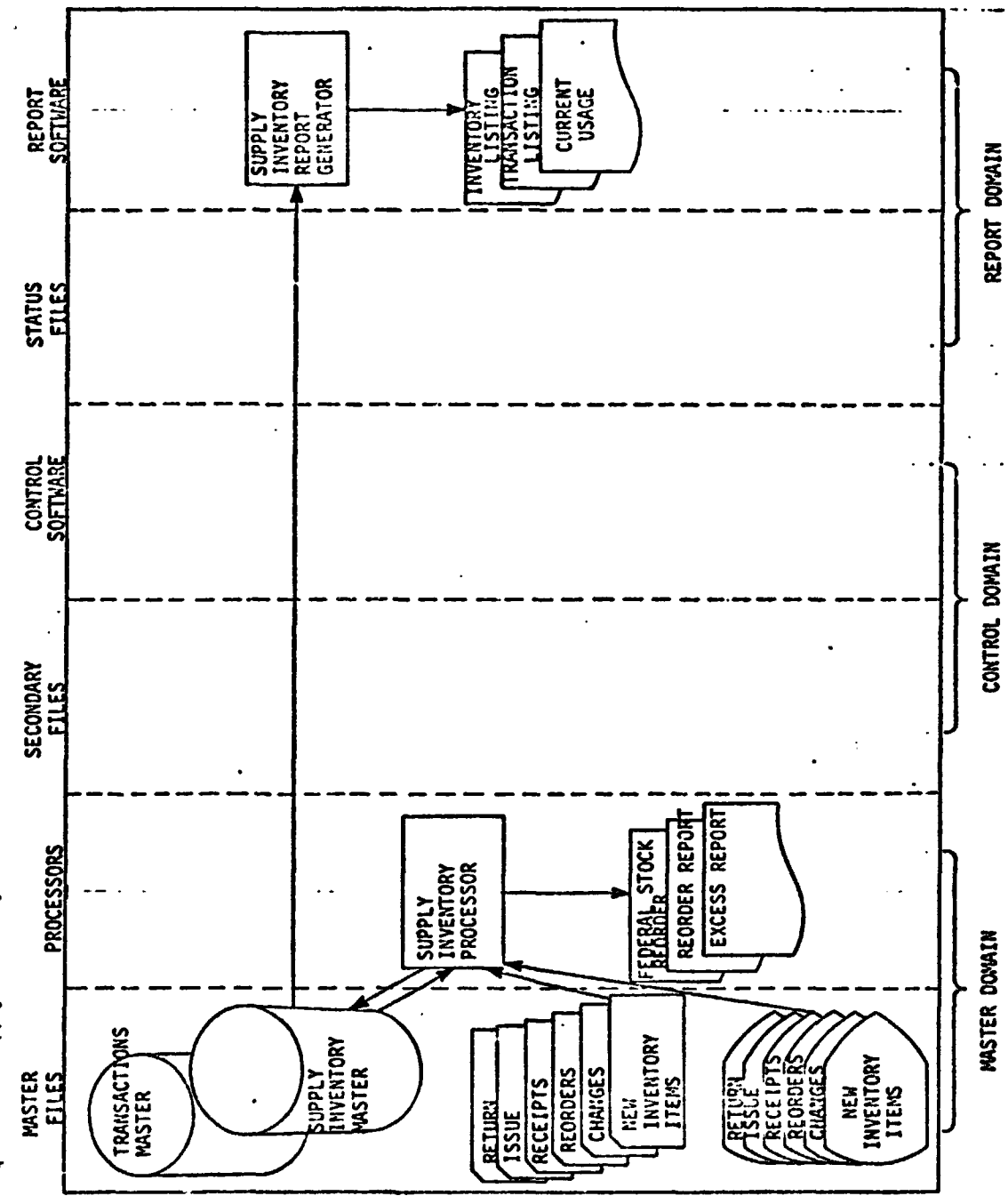
4.4.2.6.3.1 Status Files

None

4.4.2.6.3.2 Report Software

The Supply Inventory Report Generator will generate three types of reports: inventory listing, transaction listing, and current usage. These reports are generated from the Supply Inventory Master and Transaction Master files. These reports may be by manufacturer part number, control number, part name/description or any other meaningful order. The reports generated may be listings of the entire file or of a specified portion of it.

4.4.2.6 Supply Inventory



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4.4.2.7 User Software

User software is that software not directly associated with the simulation or in support of the simulation.

4.4.2.7.1 Master Domain

4.4.2.7.1.1 Master Files

The master files for the user software will consist of modules of source code. The source may be in any programming language supported by the vendor.

4.4.2.7.1.2 Processors

The processors associated with user software are all vendors supplied and include an update processor to maintain the source modules, language processors to compile the source, and a linking loader to build the load modules. The input to the update processor, either to create a new source module or modify an existing source module, can come from CRT's or cards. In addition to the generation of the object modules, the language processors will also generate listings of the source.

4.4.2.7.2 Control Domain

4.4.2.7.2.1 Secondary Files

The files associated with the control domain are the object modules generated by the language processors, and the executable load modules generated from the object modules by the linking loader.

4.4.2.7.2.2 Control Software

None

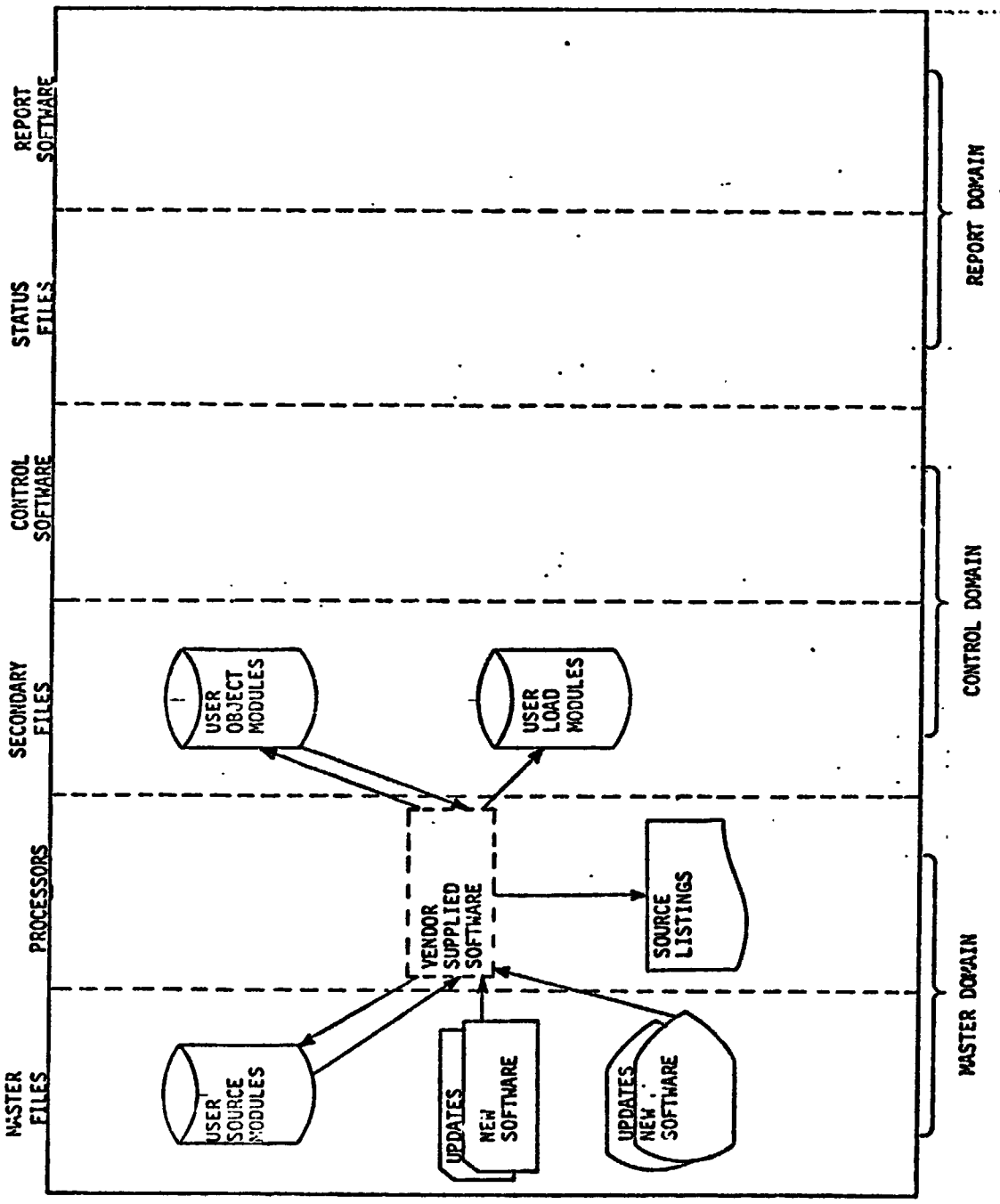
4.4.2.7.3 Report Domain

4.4.2.7.3.1 Status Files

None

4.4.2.7.3.2 Report Software

None



4.4.2.7 User Software

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4.4.2.8 Discrepancy Reports

The Discrepancy Report System will provide a means of monitoring the status of discrepancy reports (DR's).

4.4.2.8.1 Master Domain

4.4.2.8.1.1 Master Files

The DR Master file will contain all the pertinent information associated with each DR, such as DR number, date written, simulator effected (MBTS, FBTS), system effected, type of DR, DR statement, person who wrote the DR, person assigned the DR status, SCR's associated with each DR, etc.

The System Responsibility file will contain the name of the responsible person for each system of each simulator.

4.4.2.8.1.2 Processor

The DR will be put into the system via a CRT by the originating individual. At this time the DR Processor will assign a number to the DR and assign the DR to the person responsible for the effected system. Any changes to the DR or system responsibility will also be entered via a CRT. The DR status and associated SCR's will be maintained with input from the DR, Mod, and SCR Status file.

4.4.2.8.2 Control Domain

4.4.2.8.2.1 Secondary Files

None

4.4.2.8.2.2 Control Software

None

4.4.2.8.3 Report Domain

4.4.2.8.3.1 Status Files

DR, Mod, and SCR Status File

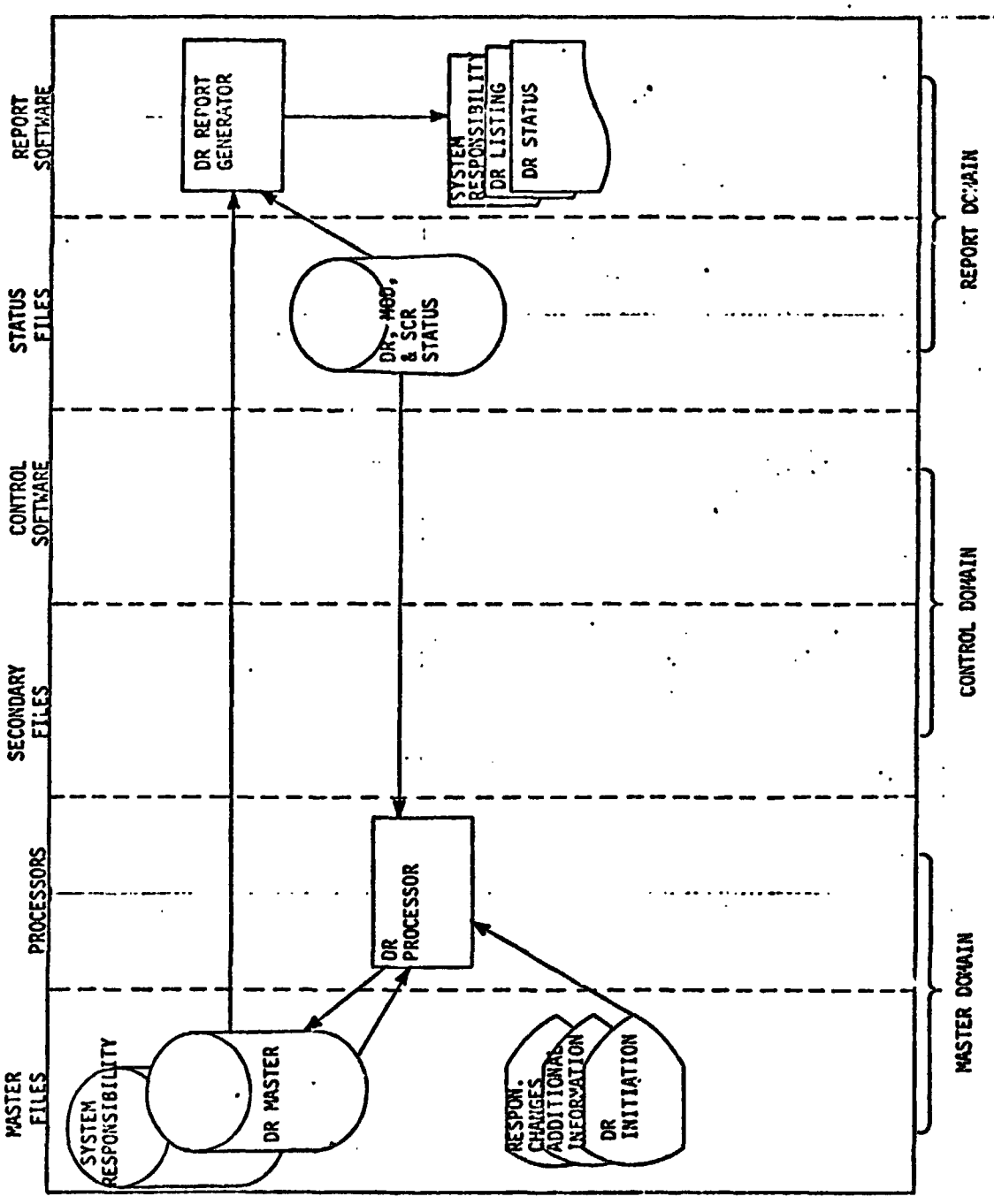
The information contained in the DR, Mod, and SCR Status File

(See Section 4.4.2.1.1.1) is incorporated into the DR master file for use in generating the DR Status Report.

4.4.2.8.3.2 Report Software

The reports generate utility data in the DR Master and System Responsibility files. The reports may be concerned with the entire file or a specified portion of it. Three reports are generated by the system: system responsibility, DR listing, and DR status. The system responsibility report is a listing of the System Responsibility file and may be generated by system, simulator or individual. The DR listing will contain a list of all associated SCR numbers which may be generated for specified DR's. This listing would serve as the documentation of a DR that has been cleared and is no longer required in the system. The DR status report gives the ability to track DR's through the system. DR's could be separated by status, system, responsible individual, etc. Status information on specific DR's may be requested from CRT's and displayed in real-time.

4.4.2.8 Discrepancy Reports



4.4.2.9 Modifications

This system will provide a means of monitoring the status of all modifications (mods) within the system.

4.4.2.9.1 Master Domain

4.4.2.9.1.1 Master Files

The Modification Master file will contain all pertinent information associated with each mod. This information shall include: mod number, description, schedule dates, DR's, and SCR's associated with each mod.

4.4.2.9.1.2 Processors

New mods and changes to existing mods, such as schedule dates, will be input to the Modification Processor via card or CRT. The mod status and associated SCR's will be maintained with inputs from the DR, Mod, and SCR Status file.

4.4.2.9.2 Control Domain

4.4.2.9.2.1 Secondary Files

None

4.4.2.9.2.2 Control Software

None

4.4.2.9.3 Report Domain

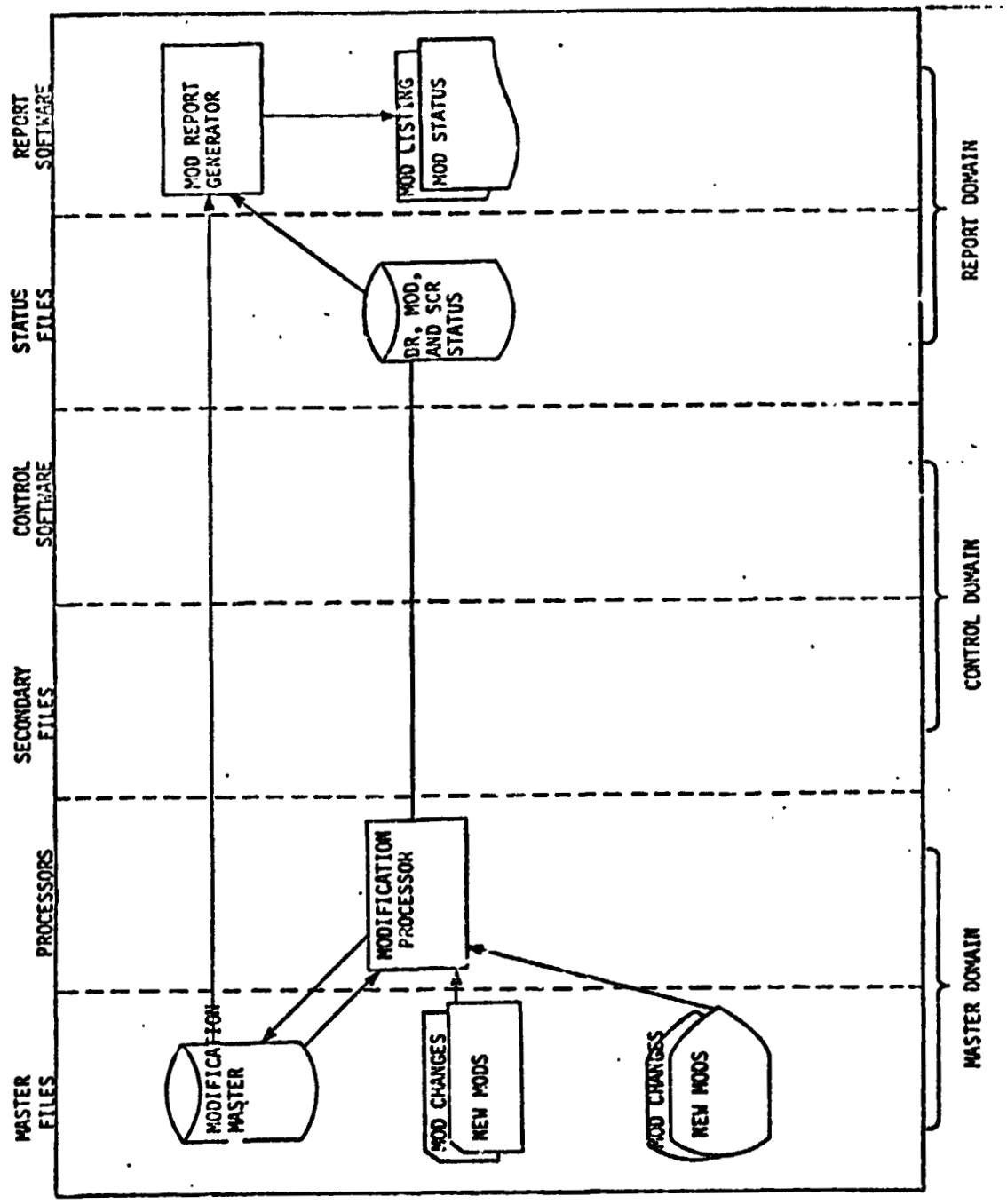
4.4.2.9.3.1 Status Files

The information contained in the DR, Mod, and SCR Status file (See Section 4.4.2.1.1.1) is incorporated into the Modification Master file for use in generating the Mod Status Report.

4.4.2.9.3.2 Report Software

The reports generated utilize data contained in the Modification Master file. These reports may concern the entire file or any specific mod. Two reports are generated: the mod listing and the mod status. The status for any specified mod could be requested from any CRT and displayed in real-time. Contained in the mod listing will be all associated SCR numbers.

4.4.2.9 Modifications



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4.4.2.10 Software Change Requests

This system will provide the means of monitoring software change requests (SCR's).

4.4.2.10.1 Master Domain

4.4.2.10.1.1 Master Files

The SCR Master file will contain the SCR update. Contained in this file will be additional information such as the individual writing the SCR, date, and DR or mod with which the SCR is associated.

4.4.2.10.1.2 Processors

The SCR will be put into the system via CRT or cards. The SCR processor will then assign a number to the SCR. Any SCR on the SCR master that is in test status may be modified through the SCR processor. The SCR status will be maintained with input from the DR, Mod, and SCR Status File.

4.4.2.10.2 Control Domain

4.4.2.10.2.1 Secondary File

None

4.4.2.10.2.2 Control Software

None

4.4.2.10.3 Report Domain

4.4.2.10.3.1 Status Files

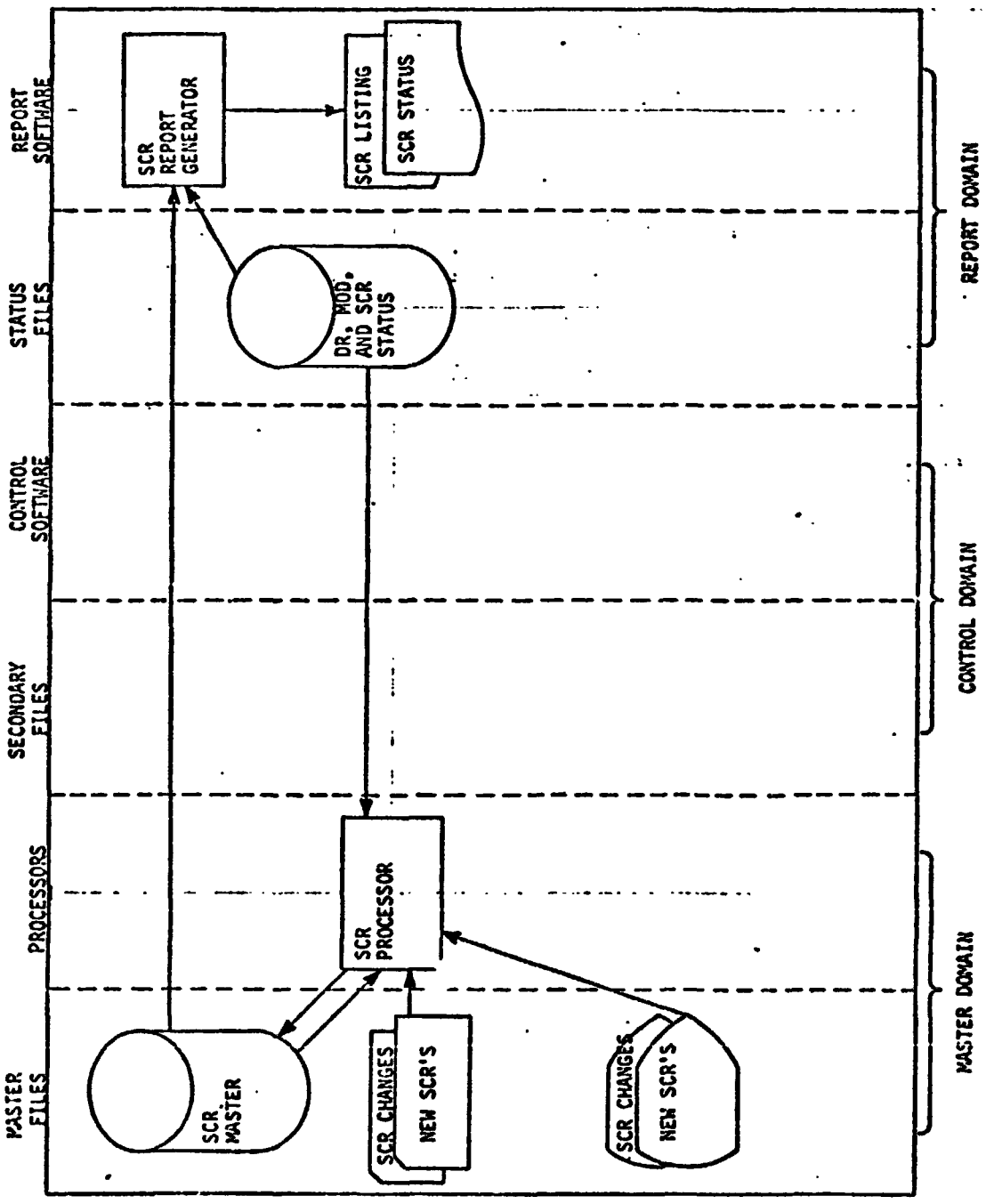
The information contained in the DR, Mod and SCR Status File (See Section 4.4.2.1.1.1) is incorporated into the SCR master file for use in generating the SCR status report.

4.4 2.10.3.2 Report Software

The reports generated utilize the data contained in the SCR master file. The reports may be concerned with all SCR's, SCR's associated with a particular DR or mod, or individual SCR's. Two reports are generated: SCR

listings and SCR status reports. The SCR listing will serve as documentation for DR's and mods that have been incorporated into the simulator system.

4.4.2.10 Software Change Requests



4.4.2.11 Simulator Hardware Documentation

This system will provide a means of monitoring the status of Hardware Change Notices (HCN's) and changes to the wire list.

4.4.2.11.1 Master Domain

4.4.2.11.1.1 Master Files

The two master files associated with simulator hardware documentation are the HCN Master and the Wire List Master. The HCN Master will contain all the HCN's that are in the process of being implemented with the current status. The Wire List Master will contain the current wire lists.

4.4.2.11.1.2 Processors

The HCN Processor maintains the HCN Master file by adding HCN's, changing HCN's or changing the status of HCN's. HCN's may be added or changed via CRT or cards. The status change may be entered via CRT or cards or if the HCN is associated with a software mod or DR, the status change can be from the DR, Mod, and SCR Status file. When an HCN status is changed to acceptance, the wire list changes associated with it are written to a secondary file to be input to the Patching and Schematics Processor. The Patching and Schematics Processor utilizes this file to update the Wire List Master file.

4.4.2.11.2 Control Domain

4.4.2.11.2.1 Secondary Files

A secondary file of wire lists changes is generated by the HCN Processor and used by the Patching and Schematics Processor to update the Wire List Master file.

4.4.2.11.2.2 Control Software

None

4.4.2.11.3 Report Domain

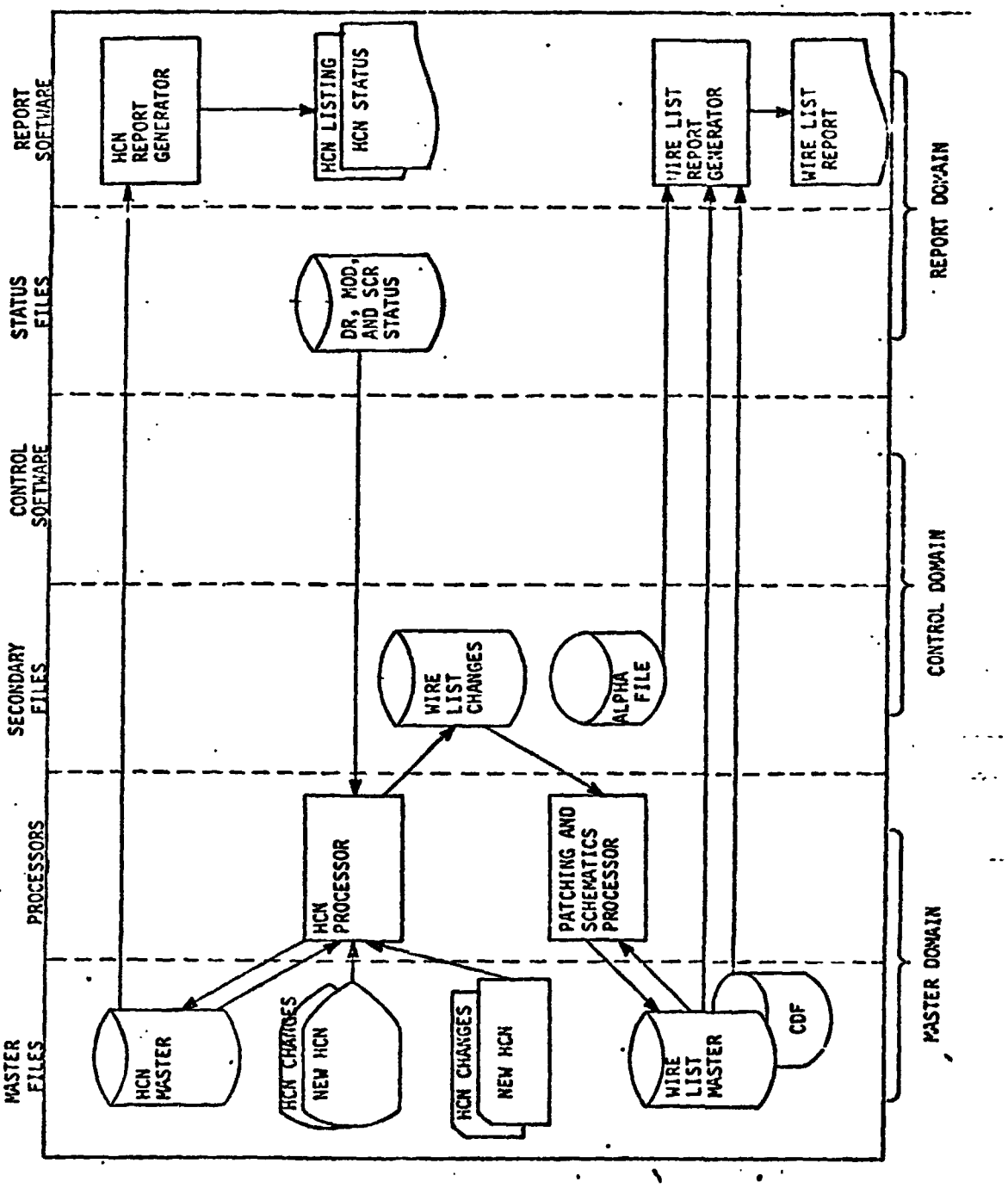
4.4.2.11.3.1 Status Files

The information contained in the DR, Mod and SCR Status File (See Section 4.4.2.1.1.1) is used to update the HCN status in the HCN Master file for those HCN's associated with software mods and DR's.

4.4.2.11.3.2 Report Software

The HCN Report Generator utilizes information from the HCN Master file to generate HCN listings and an HCN status report. The Wire List Report Generator utilizes the Wire List Master file to generate the wire list report. Both of these report generators may utilize the entire file associated with it or any specified portion of the file. Additional information for the Wire List Report is obtained from the CDF and the Alpha file.

4.4.2.11 Hardware Simulation Documentation



5.0 Cost Analysis

A cost analysis was performed as part of the baseline effort. The cost data reflects the simulator configuration of the baseline configuration defined in sections 3.0 and 4.0. Where required, quotes were obtained from vendors for materials and subcontracts. Material and labor dollars were extrapolated to the center of effort of each crew station development so that the cost reflects the value of dollars during the procurement time frame, except for the SCC related costs which were based on present quotes. The SCC is scheduled to be procured much earlier than the remainder of the SMS and cost escalation was assumed to be negligible. The software costs were based on the experience of the SLS program, which had similar documentation, program control and programming language distribution to those specified and envisioned for the SMS. Hardware material and manufacturing costs were based on complexity estimates to similar components and systems as well as quotes from vendors. Hardware design labor was based on sketch and drawing counts.

The cost for the SMS at the program level WBS is as follows:

	Title	Cost
WBS 1.0	Motion Base Crew Station	$ 14,900,000
WBS 2.0	Fixed Base Crew Station	9,254,000
	TOTAL	$ 24,154,000

Not included in this total are the costs of the SCC, visual, and GFP. The DCE costs are included in the totals since this area is in doubt as to which contract will procure the equipment.

Costs to the next level WBS breakdown are shown on Figure 5-1 for the MBCS and Figure 5-2 for the FBCS. The WBS organization is based on revision A of the SMSR. Some cost reductions can be made at the expense of increasing operating costs by deleting requirements which are not essential to the training requirements. These potential reductions are tabulated below.

a) Deletion of the non-essential areas of the Data Management System will result in a cost reduction of $163,000 in WBS 1.8. An associated reduction of approximately $550,000 is obtainable in the SCC contract by this deletion.

b) Deletion of the Record/Playback requirements will result in a deletion of $105,000 in WBS 1.8.

The above reductions will make the effort of the instructors and maintenance and modification personnel more difficult and require more operational personnel, however, probably no more so than on past mission simulators.

During the process of the cost analysis, requirements have been reduced from the Revision A version of the SMSR in the interests of

economy. However no requirements have been reduced which will affect the fidelity of training or the instructors ability to function properly.

Some of these reduction in requirements included,

a) Changing the IOS CRT requirements from a color, stroke writing, and vector rotation system to a black and white raster scan graphic system

b) Off-loading some of the SCC computation effort to the mini computer complex.

c) Reducing the documentation requirements in some areas.

Further changes were incurred during the final update of this report. Cost changes which have been incorporated into this release include the following:

a) Revision of the Voice Communication System

b) Addition of a fifth ABES engine to the Aural Cue System

c) Deletion of Advanced Training Features

d) Redesign of the DP&S including additional cost incurred by changing the IOS CRT repeaters from GFP to contractor provided

e) Miscellaneous IOS changes

f) Deletion of the full scale Crew Station Mockup.

g) Deletion of the classroom terminal

h) Addition of Launch Vehicle Bending Software

i) Addition of Launch Vehicle Slosh Software

j) Miscellaneous Change to the Application Software

WBS	Title	Sell Price
1.1	Crew Station	$ 1,452,000
1.2	Instructor Operator Station	421,000
1.3	Ancillary Equipment	327,000
1.4	On-Board Computers	966,000
1.5	Computer Complex	367,000
1.6	Digital Conversion Equipment	1,125,000
1.7	Visual	N/A
1.8	Software	3,097,000
1.9	Systems Integration	829,000
1.10	Installion, Test & C/O	1,587,000
1.11	Documentation	664,000
1.12	Program Management	1,749,000
1.13	Miscellaneous	1,312,000
1.14	Spares Provisioning	282,000
1.15	Support	221,000
1.16	Motion	501,000
TOTAL		$14,900,000

Figure 5-1

MBCS WBS Level 2 Cost Summary

WBS	Title	Sell Price
2.1	Crew Station	$ 1,214,000
2.2	Instructor Operator Station	528,000
2.3	Ancillary Equipment	157,000
2.4	On-Board Computers	567,000
2.5	Computer Complex	250,000
2.6	Digital Conversion Equipment	834,000
2.7	Visual	N/A
2.8	Software	480,000
2.9	Systems Integration	148,000
2.10	Installation, Test & C/O	1,207,000
2.11	Documentation	397,000
2.12	Program Management	2,002,000
2.13	Miscellaneous	1,019,000
2.14	Spares Provisioning	262,000
2.15	Support	189,000
TOTAL		$ 9,254,000

Figure 5-2

FBCS WBS Level 2 Cost Summary

6.0 Schedule

6.1 Overview

An overall procurement schedule model and flight schedule was used as the basis for this analysis. The model is shown on Figure 6-1. In general, the simulator appears able to be developed and designed without a large risk within the time frame allocated by the model. However some problems do exist and these are discussed below under the respective work package.

It should be noted that in general the pacing item on most prototype simulators is the visual system if it is not an off-the-shelf device The SMS visual does not fall into the off-the-shelf category and may well be the pacing item. As the visual system design was not included in this study, no conclusions on the overall SMS schedule compatibility with the model can be reached other than with suitable management on the SMS contractor and NASA's part the remainder of the effort is realizable.

It was assumed in the analysis that the DCE and mini computer complex would be procured by the SMS contractor. The impact on the schedule is that an extensive factory checkout is possible with this arrangement which will make hardware alterations during test much more convenient. The alternative, if the DCE is procured by the SCC contractor, is to ship piece-meal as the equipment is assembled and perform the same type of checkout in the field. Modifications both to make the equipment function properly and due to spacecraft modifications will

become more costly to implement but the schedule would remain the same and more modifications would have to be relegated to the post-acceptance update cycle.

Progressively less risk would be incurred, particularly if the visual system is considered, if the schedule for each crew station were extended by three to six months. It is recommended that this type of extension be seriously considered if the flight dates move out prior to ATP. Additional cost would automatically be incurred if the schedule is extended. This cost might be judged unnecessary but it must be weighted against the costs which may be incurred if the SMS contractor has to extend the schedule or compress activities to maintain the original schedule. The risk also exists that the simulator as delivered will not be in a configuration suitable for training. An extended schedule would tend to minimize this risk as well as provide more time to solve the data acquisition problems which are always inherent in a simulator which is being designed concurrent with the spacecraft or aircraft.

It is assumed inherently in the schedules that the majority of the spacecraft data will be available at ATP, particularly in the crew station area and that the CTF hardware will be available prior to the end of assembly.

6.2 Motion Base Crew Station Schedule

The model for the MBCS is set up by providing one year of astronaut training prior to the first manned orbital flight. The overall

MBCS schedule is shown on Figure 6.2. A six month post acceptance modification effort is included in the schedule to incorporate spacecraft modifications which cannot be accommodated into the original schedule. This modification effort is required since the Shuttle and Orbiter CDR's will occur during the simulator development cycle and Orbiter 2 rollout is scheduled coincident with the scheduled acceptance of the MBCS. PDR's are generally scheduled for the third to the sixth month after ATP. CDR's are scheduled for the sixth to the ninth month of the program. Procurement will in general start after the individual PDR's and extend to the start of subassembly. Long lead items will have to be ordered at the earliest possible date irregardless of PDR and CDR constraints. At ATP a NASA/Contractor committee should be formed to identify and approve the procurement of the long lead items. In addition equipment which is an off-the-shelf design (e.g., DCE, basic motion) should be reviewed by the committee and released to manufacturing as soon as possible in order to support early testing and relieve the potential integration/manufacturing bottlenecks.

The fabrication/assembly cycle is scheduled for the sixth to the seventeenth months of the program. A factory test cycle of three months is planned to integrate the hardware components mechanically and electrically (up to the DCE mini computer). Subsequent to the factory test, the equipment will be shipped to JSC and re-erected. A hardware/software integration consisting of installation, system testing, Acceptance rehearsals and finally acceptance testing will continue for

seven months. Crew training will start at month 27, one year prior to the first flight. A configuration update will be made from months twenty-five to month thirty-one which will conclude the MBCS program. All GFP will be required by month 13 in order to support manufacturing and testing.

Each area of the MBCS will be discussed below and the risks and problem areas if any discussed.

6.2.1 Crew Station - The major schedule risk in the crew station area is the lead time associated with the procurement of spacecraft panel components. This problem can be compounded by data deficiencies in the area of identification of the components. The GFP Data Package should be as detailed as possible in this area to enable rapid evaluation of the procurement situation.

6.2.2 Motion - The basic motion system should be released to manufacturing as soon as possible after ATP. The visual system forward display system is a constraint to the design of the motion platform and tilt mechanism and as such the display design has to be resolved rapidly. An in-house test of the total motion systems will have to be conducted prior to shipping in order to verify performance and safety. This testing should consist of initial testing with dummy loads and progress to a full visual, crew station and motion system configuration.

6.2.3 Instructor Operator Station - Constraints to the IOS schedule are the availability of spacecraft components, GFP, and the CRT system

which today have lead times of eight months. The CRT system also constrains the Simulator Control Software which must be functioning prior to the start of Hardware/Software integration and preferably prior to the start of Systems Integration.

6.2.4 Ancillary Equipment - Ordinarily this type of equipment is not a schedule problem to the simulator development. Obviously simulator power and the CTE will be on the critical path and constrain the overall schedule if not available in a timely manner. Aural cue will require data from the vehicle test program in order to be completed and NASA should make an effort at this time to obtain, schedule and put requirements on the test program itself to obtain the required information.

6.2.5 Data Processing & Software - Perennially this area is a schedule problem and from early schedule analysis, it appears that it will be once again. The major constraints are the availability of:

a) the interface mini computers

b) the GFP flight computers and CRT system

c) flight software.

The interface mini computers currently have a lead time of one year and as such must be placed on order immediately after ATP. The GFP flight computers and CRT system should be made available 12-13 months after ATP to verify the hardware interface design which can be a lenghty process if any troubles arise. The flight software situation is that tapes for the FHF will be available to support in-plant and

system testing. However the FHF flight tapes will not support the launch, orbit and entry mission phases. The FMOF program tape schedule was not available but projecting a similar schedule as for the FHF puts their availability at the start training date. Further data on the availability of the FMOF software is required before any conclusions can be drawn, but if the projected schedule is accurate and cannot be bettered work-around plans will have to be generated such as the design of drivers to check out the simulator and support early training as well as provisioning for a heavy check out effort of the FMOF flight tapes with the simulator during the MBCS modification time frame.

6.2.6 Digital Conversion Equipment - The major constraint to the DCE area is the mini computer availability date which if ordered close to ATP presents no problems. The other constraint is ensuring an early manufacturing start which on most simulators is not a problem since all that is required is a good DCE count assuming an off-the-shelf design is used. The proposed schedule shows a normal release, i.e., completion of PDR and CDR and is compatible within the overall schedule requirements. Schedule insurance could be gained by releasing those areas which are standard designs as soon as the number required is determined.

The DCE is on the critical path and must be available prior to the start of in-house testing and hardware/software integration.

6.2.7 Mini Computer Complex - The mini computer complex is projected to have a twelve month lead time and as discussed above must be ordered immediately. One computer is required to be delivered to the SCC for check out of the SCC/mini computer interface and to check out the CRT/Mini/SCC hardware/software compatibility at the start of Systems Integration. The remaining computers are required for check out of the DCE and DP&S hardware.

6.2.8 Shuttle Systems Software - Spacecraft data availability is the only constraint in this area.

6.2.9 Simulator Applications Software - Spacecraft data availability is the only constraint in this area.

6.2.10 Simulator Control Software - Working control programs are critical to the start of Systems Integration.

6.2.11 Support Software - This area must be started early to provide the procedures and software which will be required to design, code and check out the other software.

6.2.12 Systems Integration - Systems Integration is constrained by the availability of the simulator software programs. The CRT system hardware and software is the key item to enable meaningful integration to begin. Proper emphasis on this area at the start of the program will ensure that the simulation software is available in the proper sequence.

6.2.13 Installation, Test & Demonstration - The availability of the simulator hardware and software constrains the start of this effort.

If major simulator elements, such as the OBC or C&D become a schedule problem, due to data or delivery dates, work-around plans should be instituted immediately to enable system testing to proceed and isolate the remainder of the simulator from the problem area.

6.3 Fixed Base Crew Station

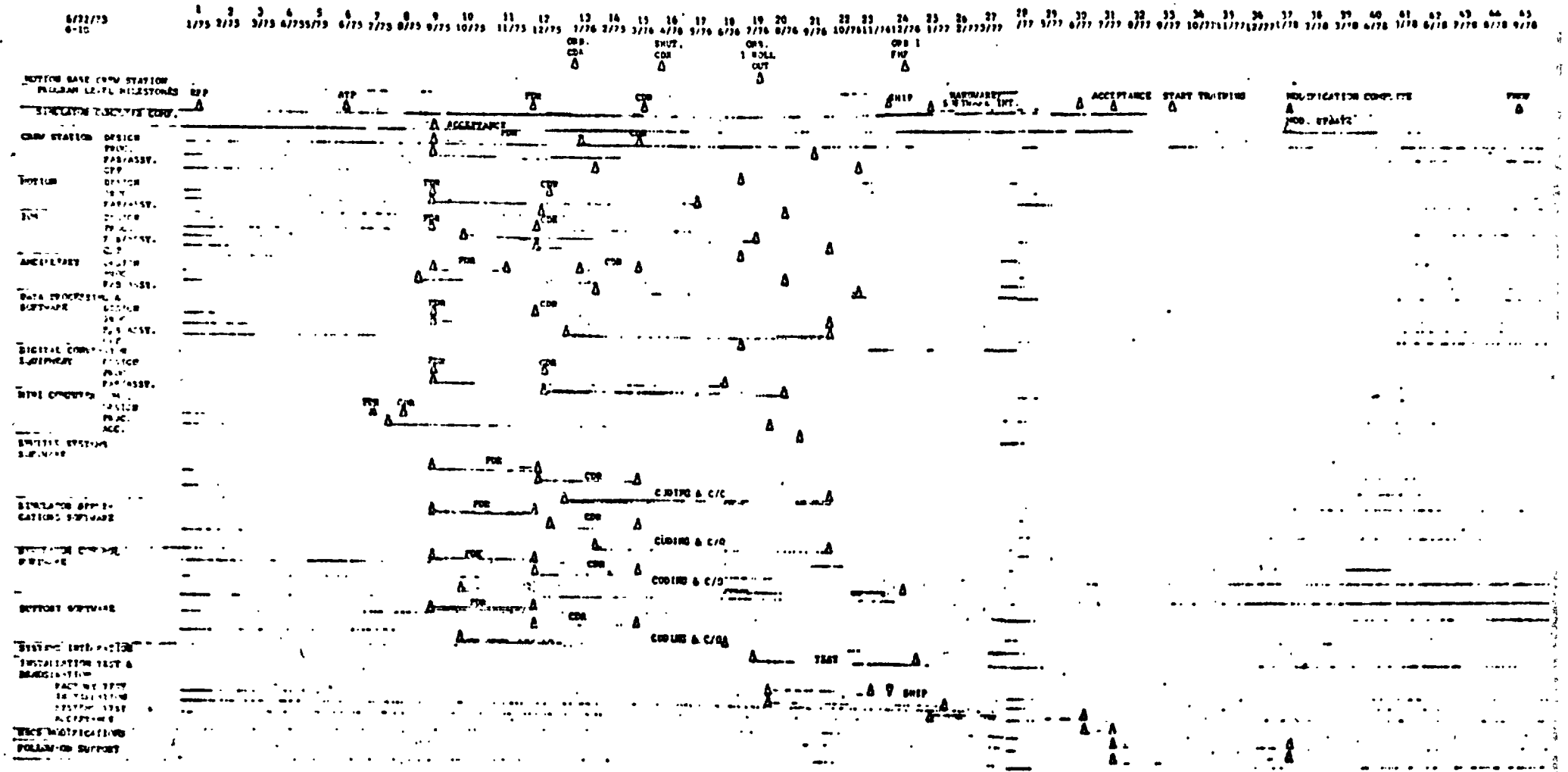
The FBCS is much less of a schedule problem than the MBCS due to the fact that a majority of the non-recurring design effort will have been accomplished. It is recommended that PDR's be conducted immediately after ATP for systems which are basically the same as the MBCS. This approach will eliminate the majority of the procurement problems and enable an early manufacturing start. If the visual system is a schedule problem it would be beneficial to start the visual preliminary design and procurement at a low level of effort prior to the official ATP of the FBCS. The overall schedule for the FBCS is shown on Figure 6-3.

LEVEL II MILESTONE CHART

W.B.S. #	END ITEM	CY 1972 1	2	3	4	CY 1973 1	2	3	4	CY 1974 1	2	3	4	CY 1975 1	2	3	4	CY 1976 1	2	3	4	CY 1977 1	2	3	4	CY 1978 1	2	3	4	CY 1979 1	2	3	4
	SHUTTLE MILESTONES					ORB. CDR	SHUT CDR		FHF			START TRAINING MBCS					FMOF				5th MOF												
								ORBITER #1 ROLLOUT				ORBITER #2 ROLLOUT					START MBCS		TRAINING														
	SIMULATION COMPUTER COMPLEX			ACCEPTANCE																													
	MOTION BASED CREW STATION		ATP																														
	PDR																																
	CDR																																
	MANUFACTURING																																
	HARDWARE/SOFTWARE INTEGRATION																																
	ACCEPTANCE																																
	MODIFICATION																																
	FOLLOW-ON SUPPORT																																
	TRAINING																																
	FIXED BASE CREW STATION						ATP																										
	PDR																																
	CDR																																
	MANUFACTURING																																
	HARDWARE/SOFTWARE INTEGRATION																																
	ACCEPTANCE																																
	FOLLOW-ON SUPPORT																																
	TRAINING																																

LEGEND: SYSTEM DESIGN; DESIGN & DRAFT; PROGRAMMING; PROCUREMENT; FABRICATION; ASSEMBLY; INTEGRATION; TEST & CAL; PACK/SHIP; CUSTOMER OR SUBCONTR. SUPPORT

FIGURE 6-1 SMS PROGRAM MILESTONES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ORB. CDA
SHUT. CDR
ORB. 1 ROLL OUT
ORB 1 FHP
NOTIONAL BASE CREW STATION PROGRAM LEVEL MILESTONES
RFP
ATP
PDR
CDR
SHIP
HARDWARE S/W INT.
ACCEPTANCE
START TRAINING
MODIFICATION COMPLETE
MOD. STARTS
FMEW
SIMULATION EXECUTIVE CONT.
ACCEPTANCE
CREW STATION
OPTICS
INS
ANCILLARIES
DATA PROCESSING & SOFTWARE
DIGITAL COMPUTER SUBSYSTEM
MASS MEMORY
SIMULATION APPLICATIONS SOFTWARE
SUPPORT SOFTWARE
SYSTEMS INTEGRATION
INSTALLATION TEST & READINESS REVIEW
FACTORY TEST
INSTALLATION
SYSTEM TEST
ACCEPTANCE
MCC MODIFICATIONS
FOLLOW-ON SUPPORT
CODING & C/O
CODING & C/O
CODING & C/O
TEST
SHIP

FIGURE 6-2 MCC PROGRAM SCHEDULE

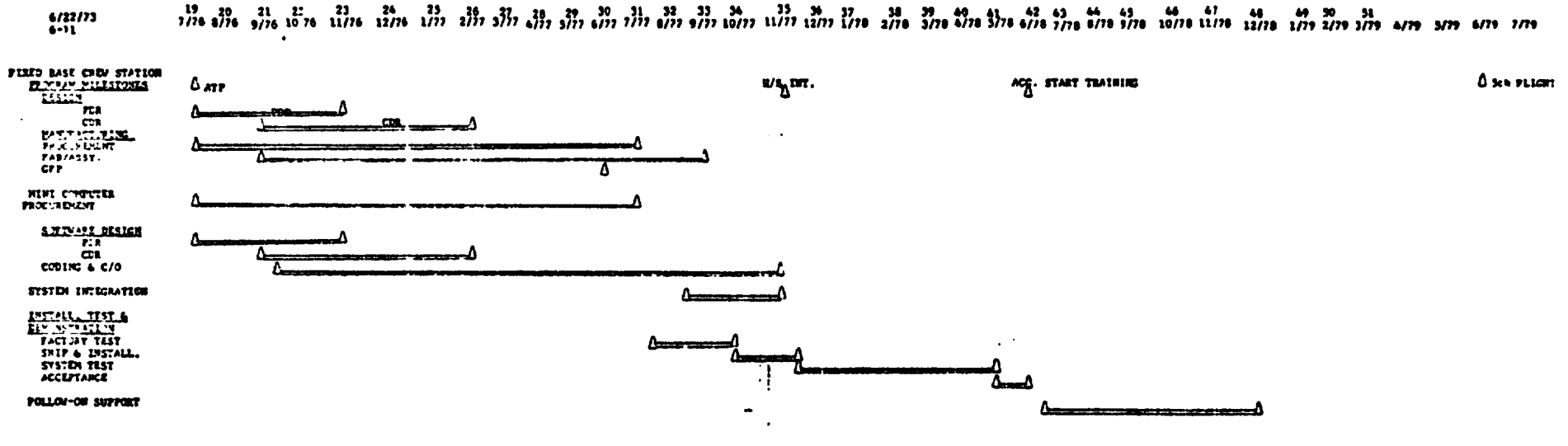

FIGURE 6-3 FSCS PROGRAM SCHEDULE

SMS

BASELINE DEFINITION

REPORT

ADDENDUM A

CREW STATION PANEL LOCATIONS

AND OUTLINE DRAWINGS

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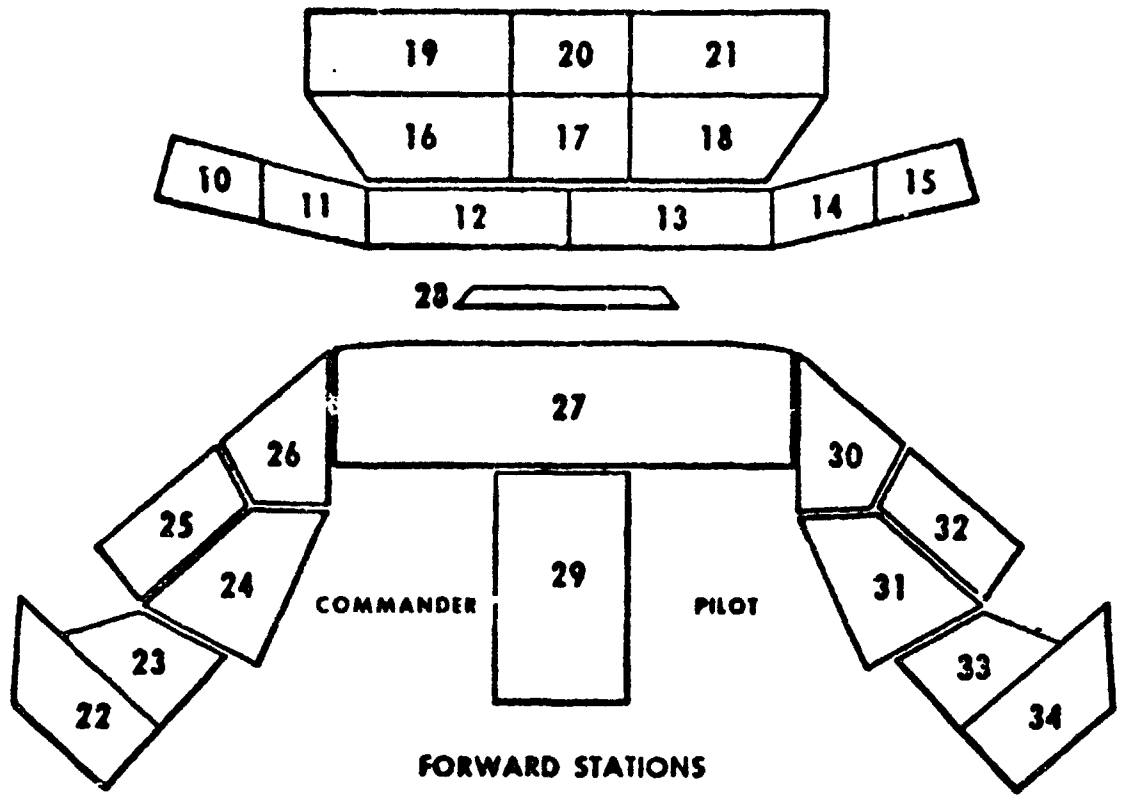
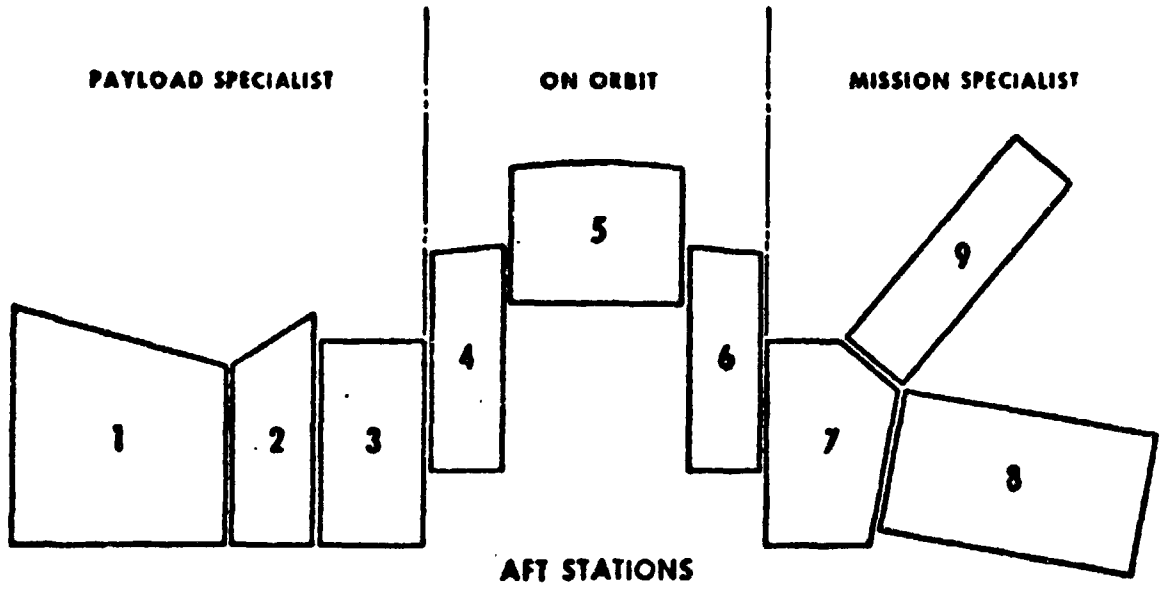


FORWARD STATIONS



AFT STATIONS

NUMBERS OF PANELS ARE FOR REFERENCE ON THIS DRAWING ONLY

PANELS 1, 2 AND 3 NOT SHOWN

SPACE DIVISION
NORTH AMERICAN ROCKWELL

ORBITER FLIGHT DECK,
PANEL CONFIGURATION - SRB

SIZE	DOCUMENT NO.	DRAWING NO.
J	03953	VL70-730100

SHEET 1 OF 2

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PANEL 1

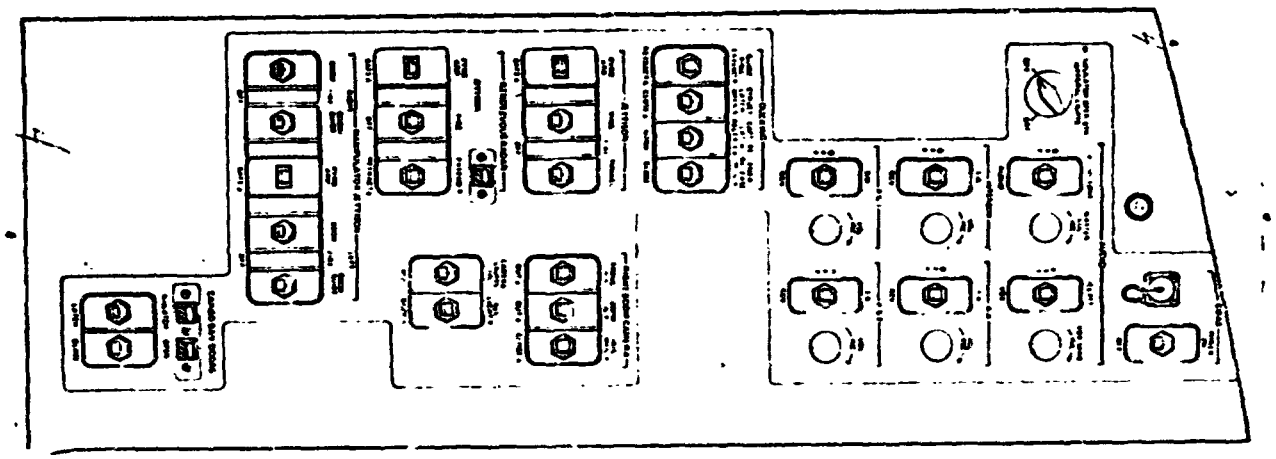
TBD

PANEL 2

TBD

PANEL 3

TBD



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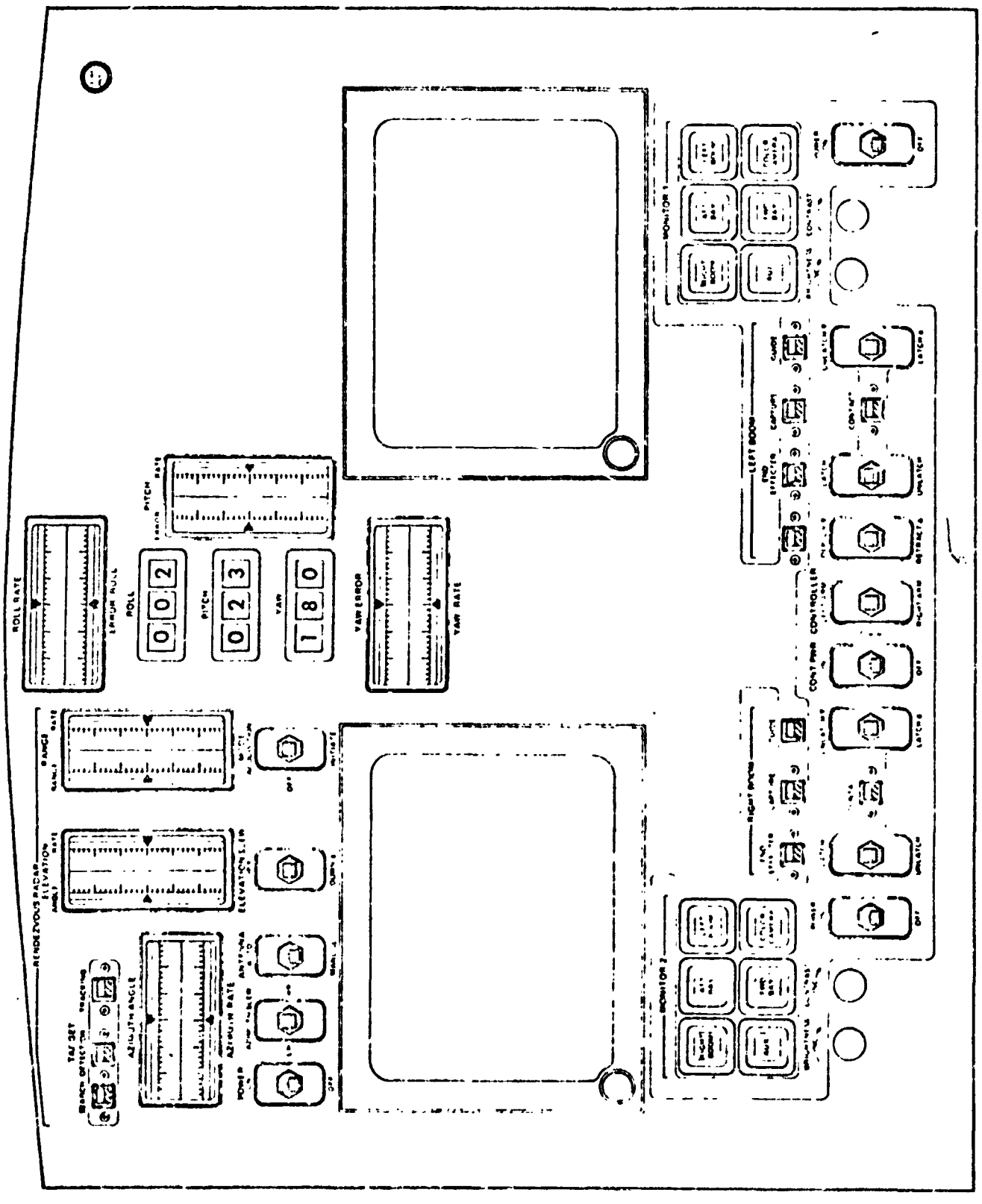

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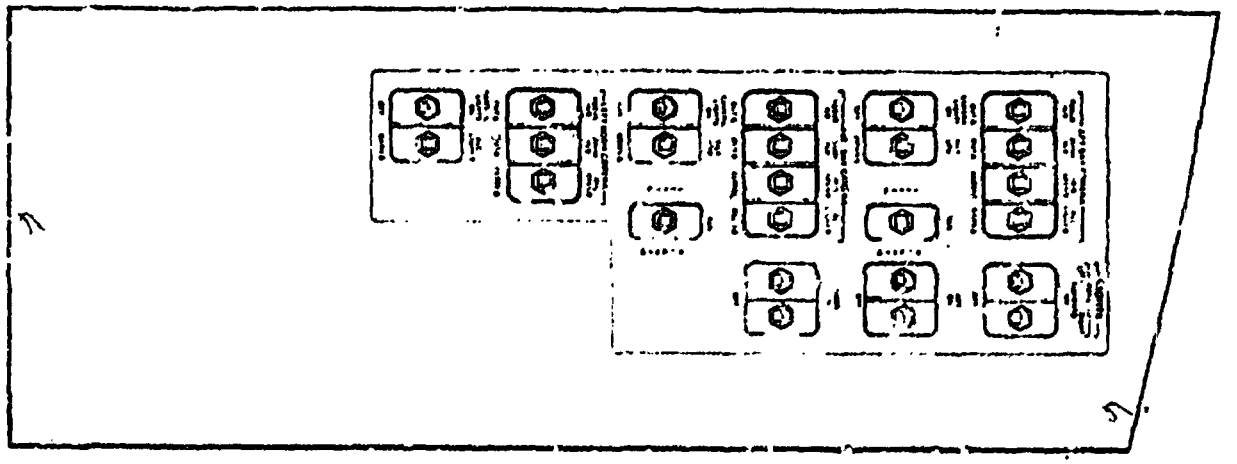

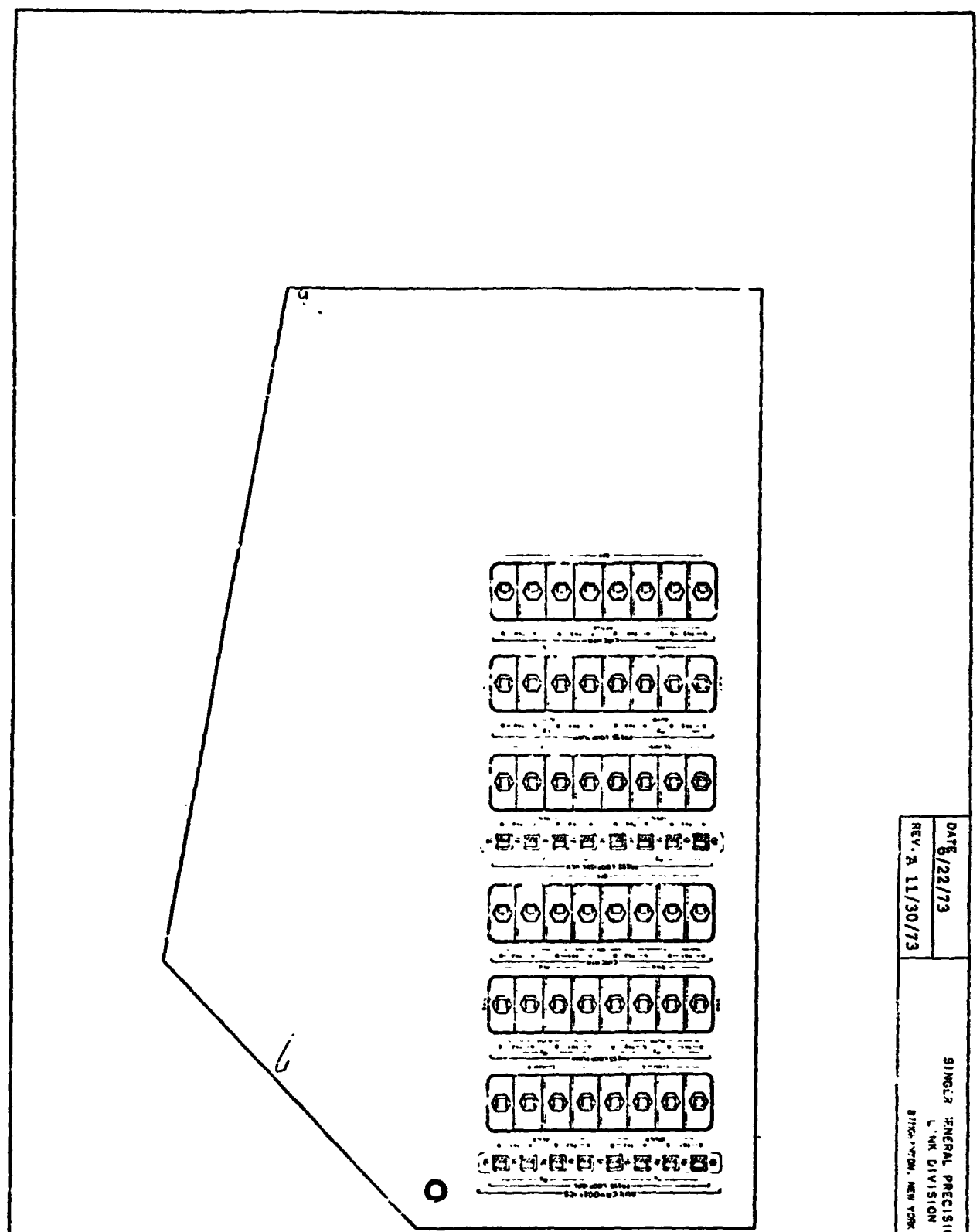

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LINK DIVISION
BINGHAMTON, NEW YORK

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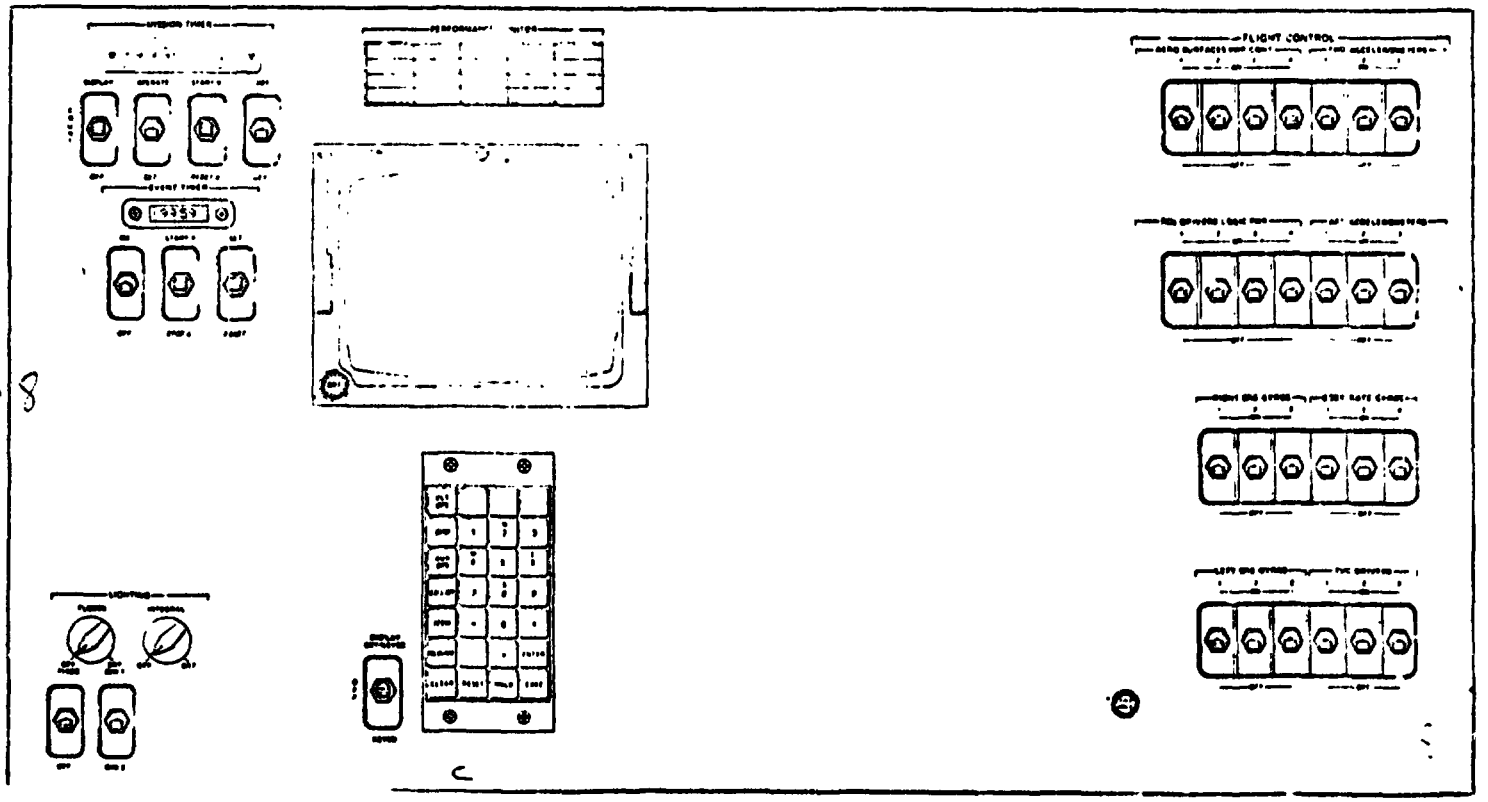
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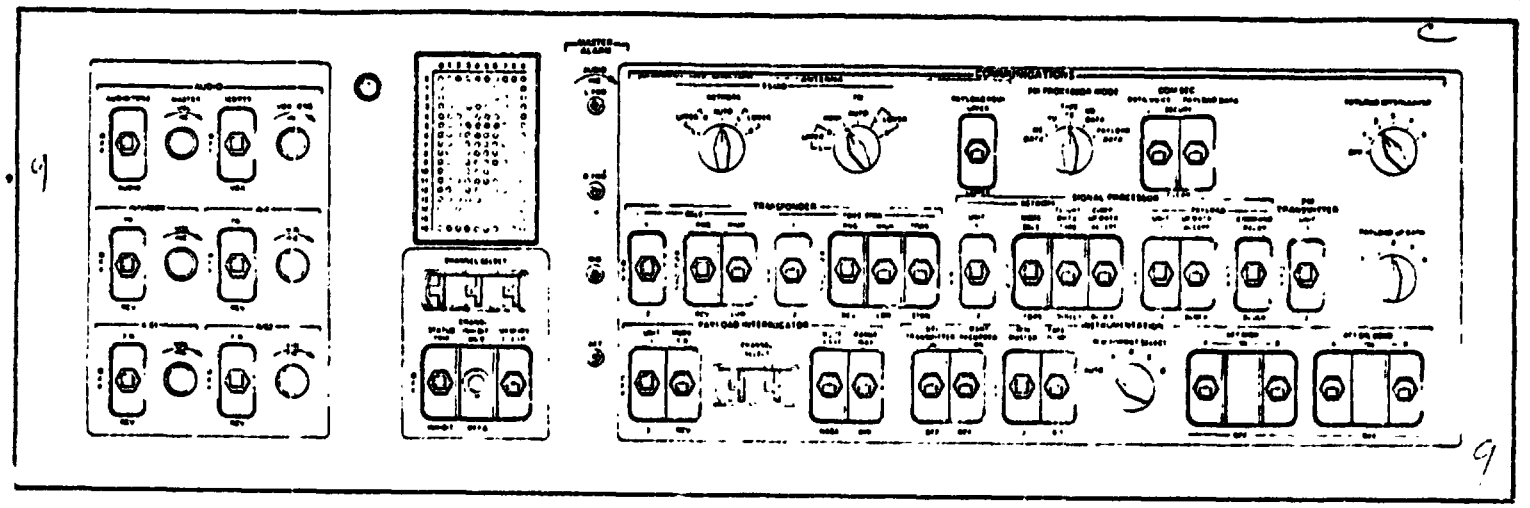

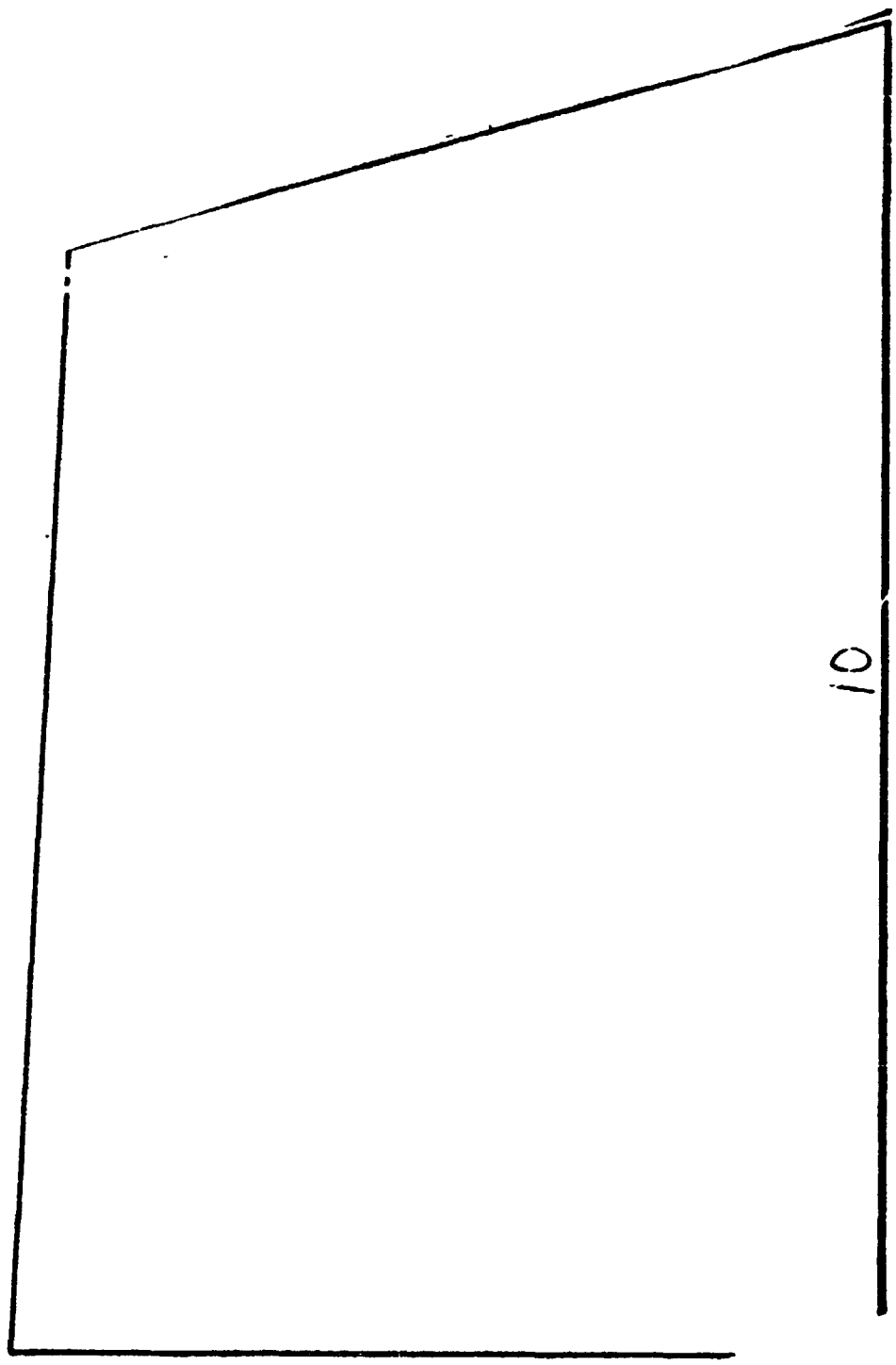
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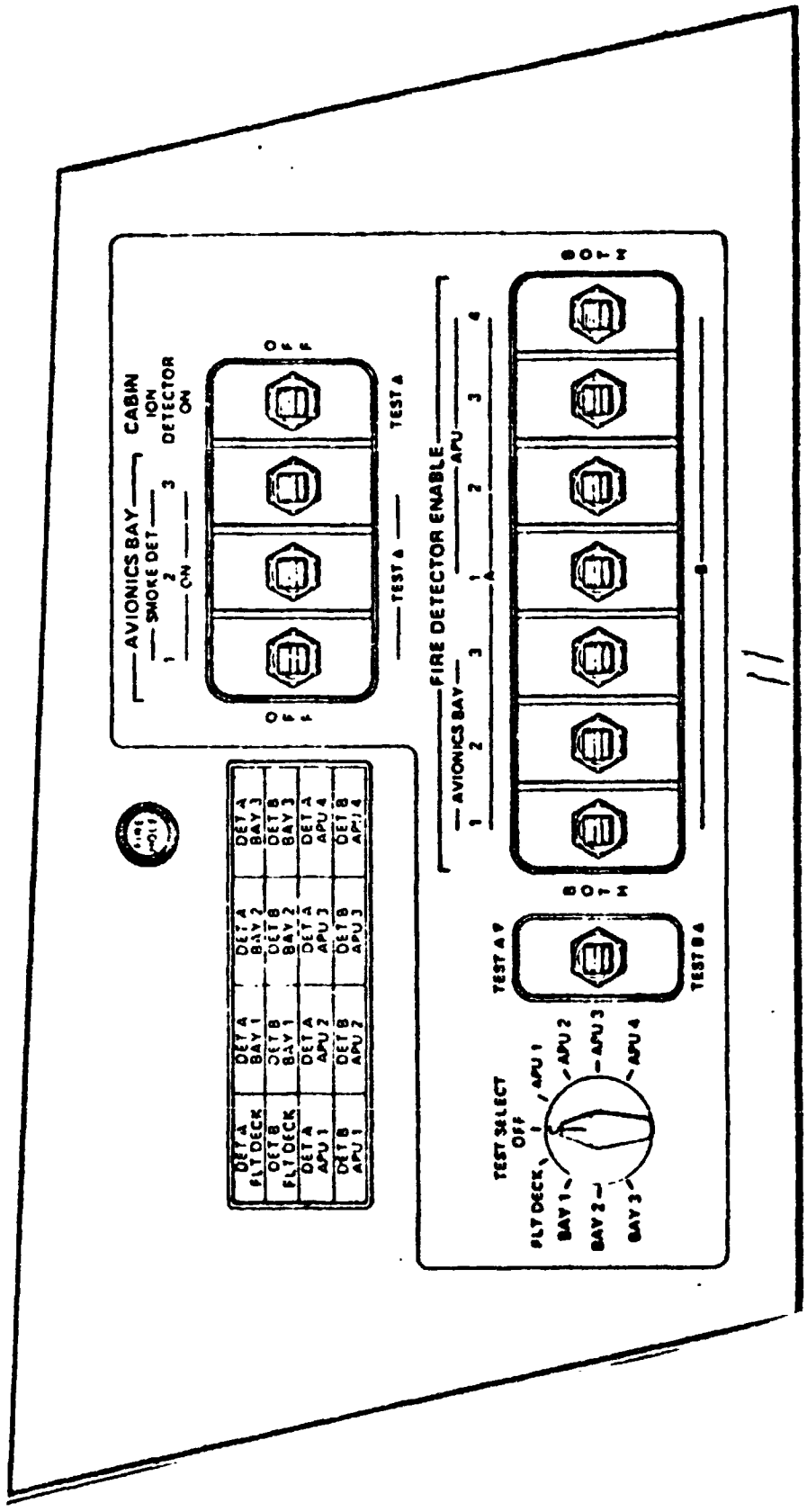

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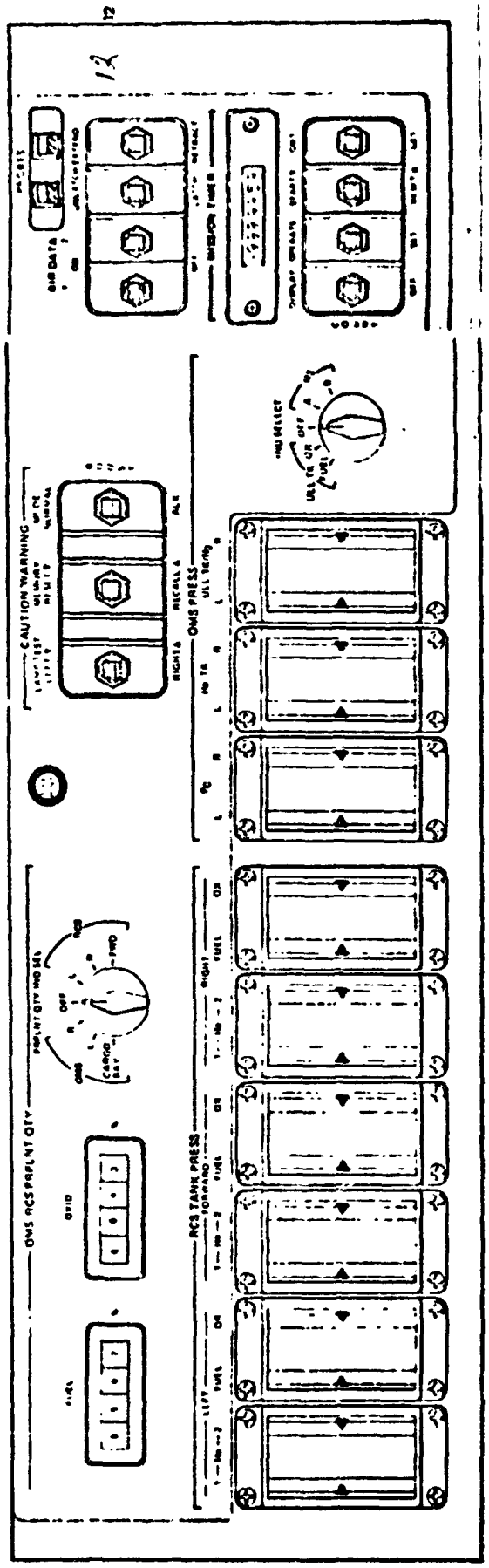
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OMS PRESS
RCS TANK PRESS
OMS RCS PROPLNT QTY
PROPLNT QTY MNTR SEL
FUEL
OXID
OFF
FUEL
OXID
LEFT
RIGHT

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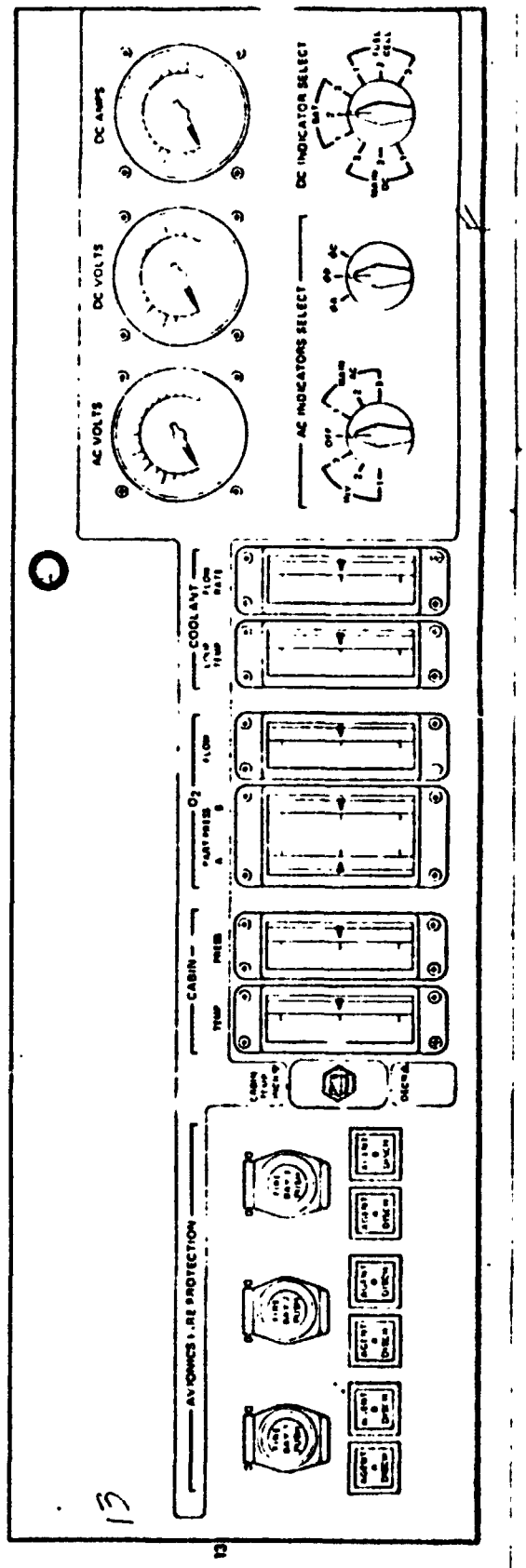

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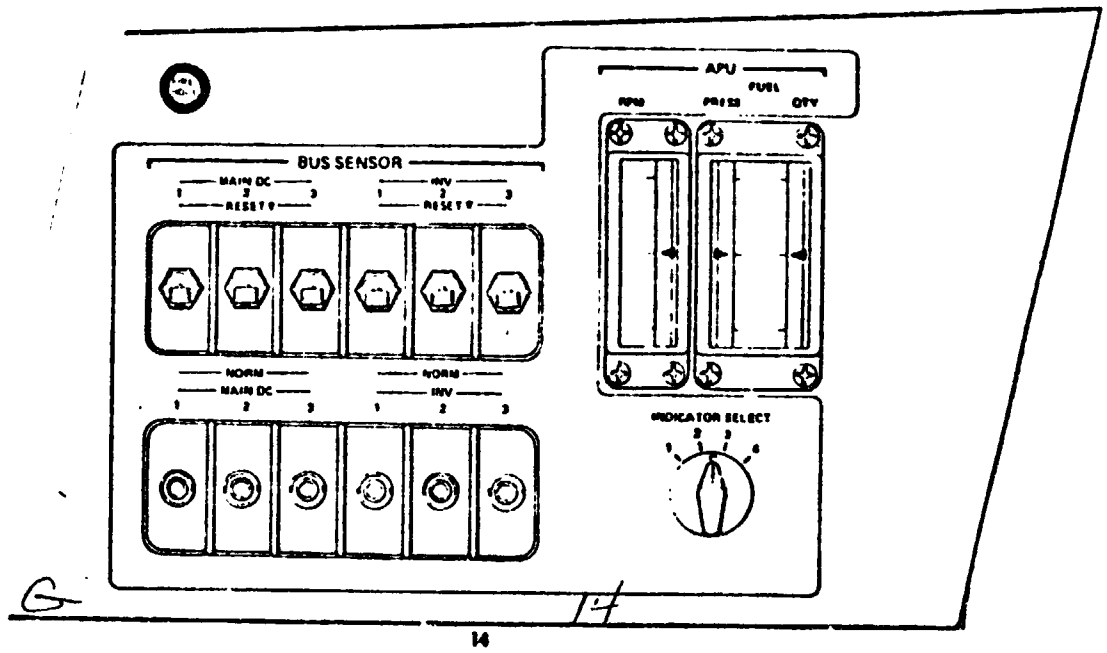

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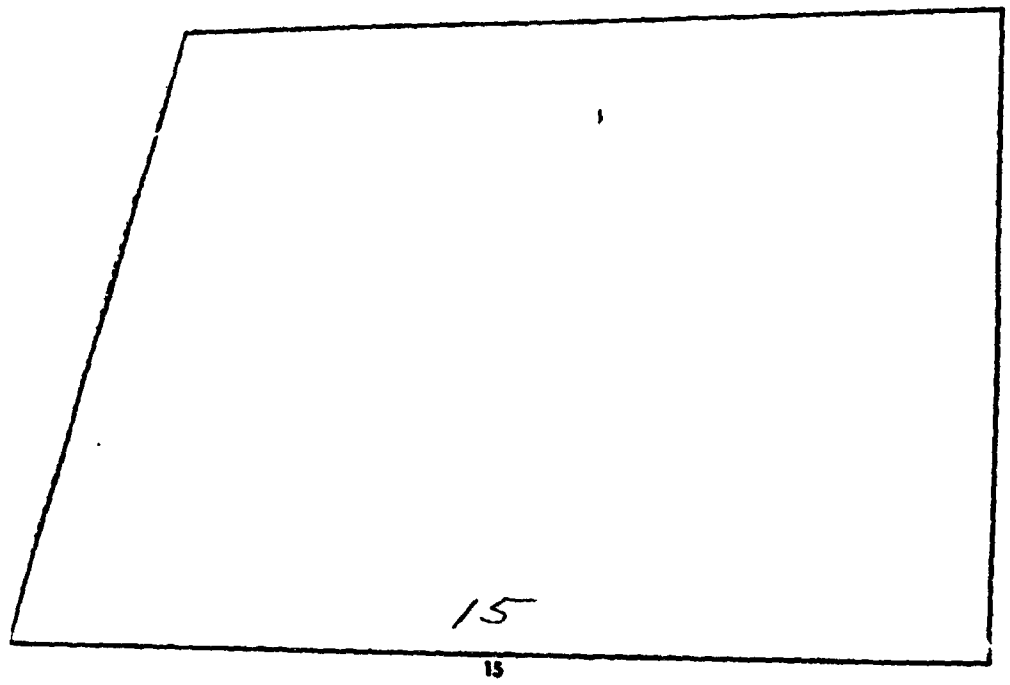

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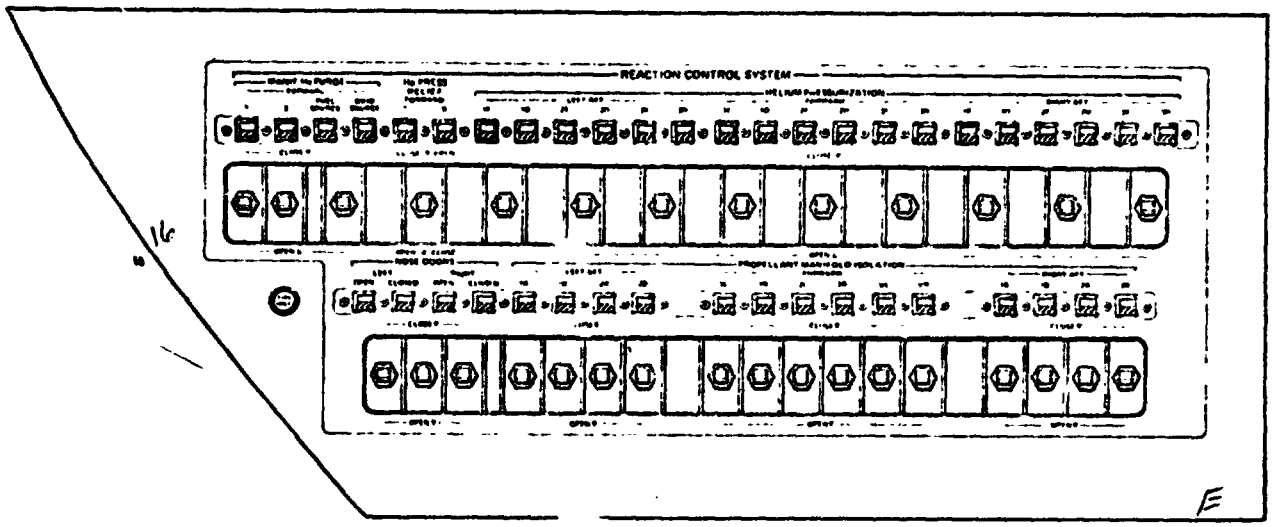
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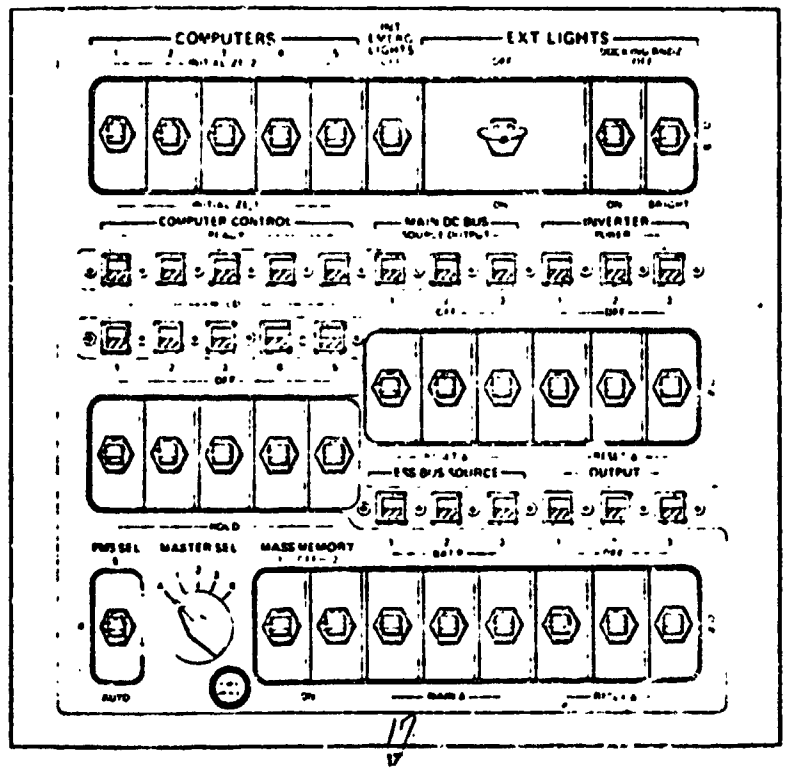
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EXT LIGHTS
COMPUTER CONTROL
MAIN DC BUS
INVERTER
OUTPUT
MASTER SEL
MASS MEMORY
AUTO

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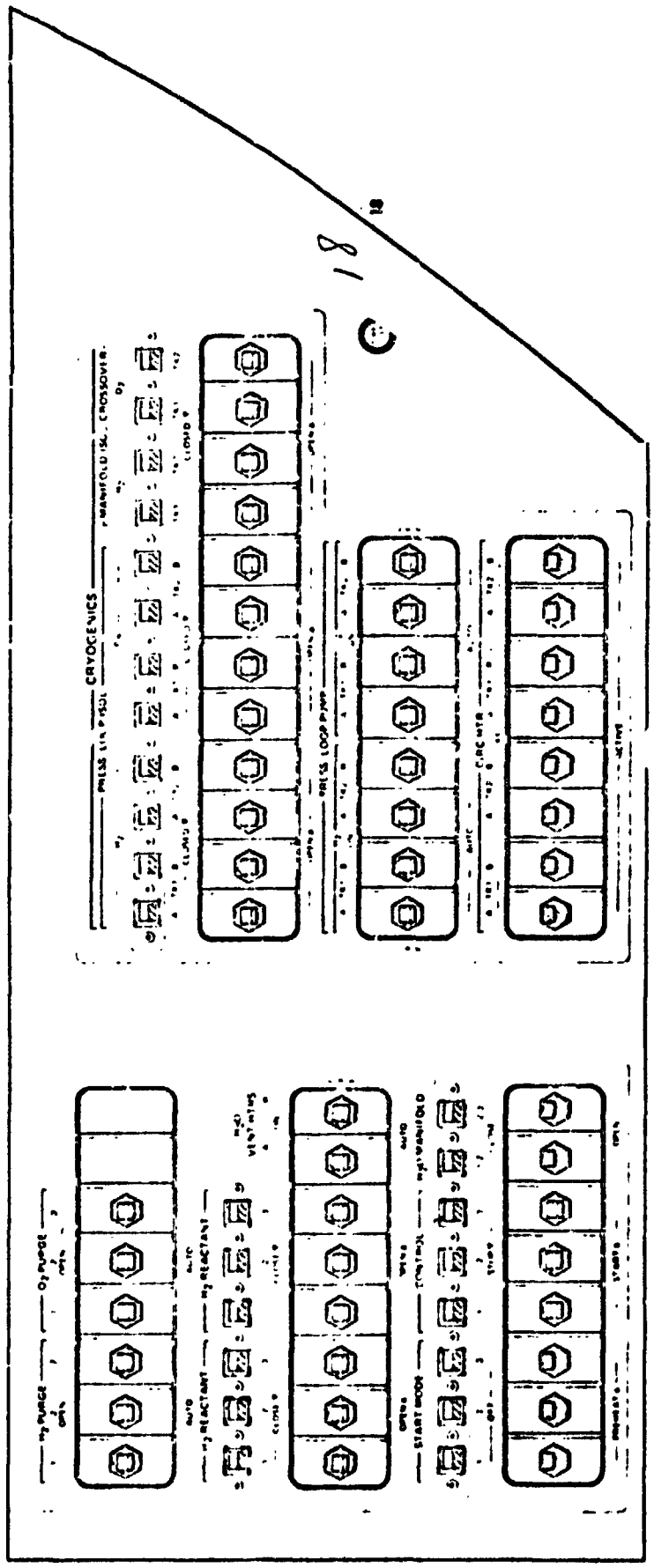

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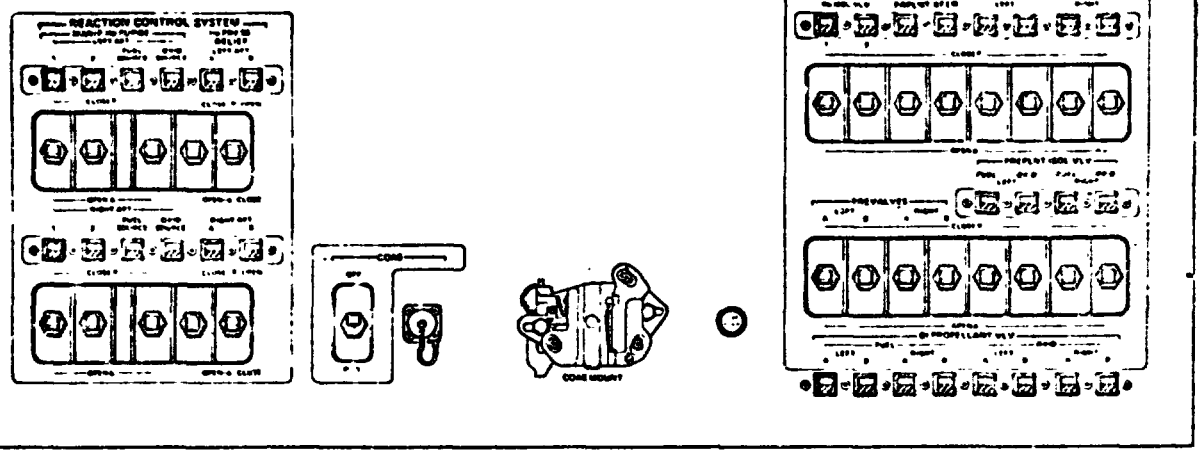

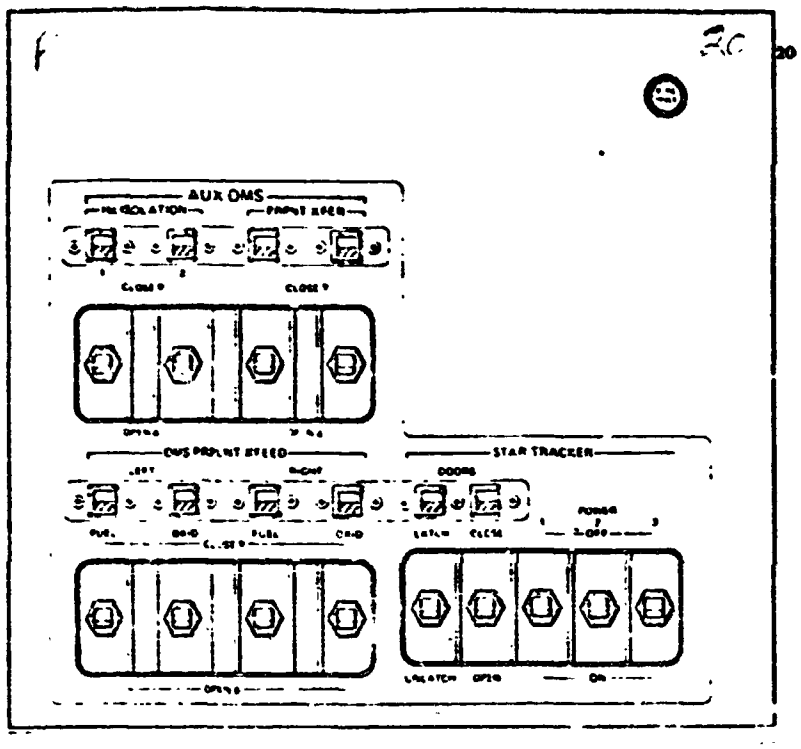
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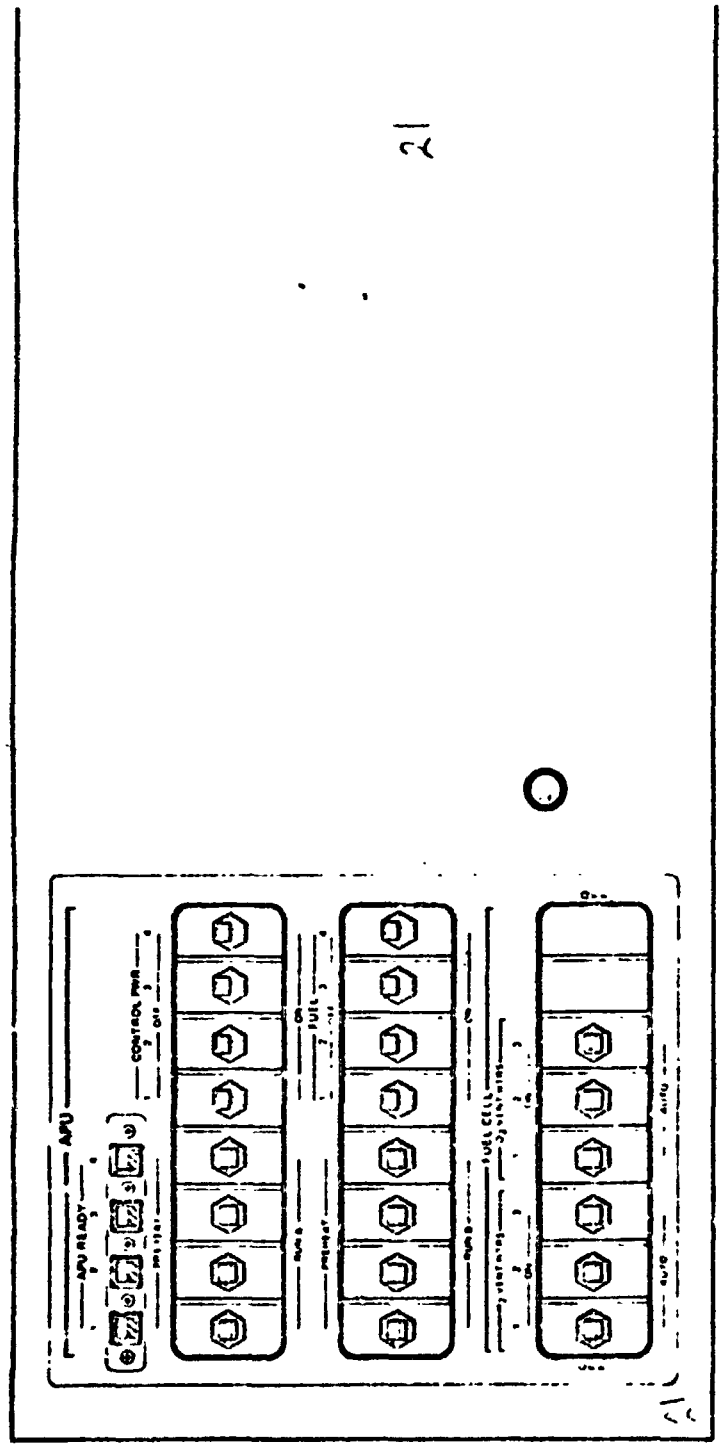
ON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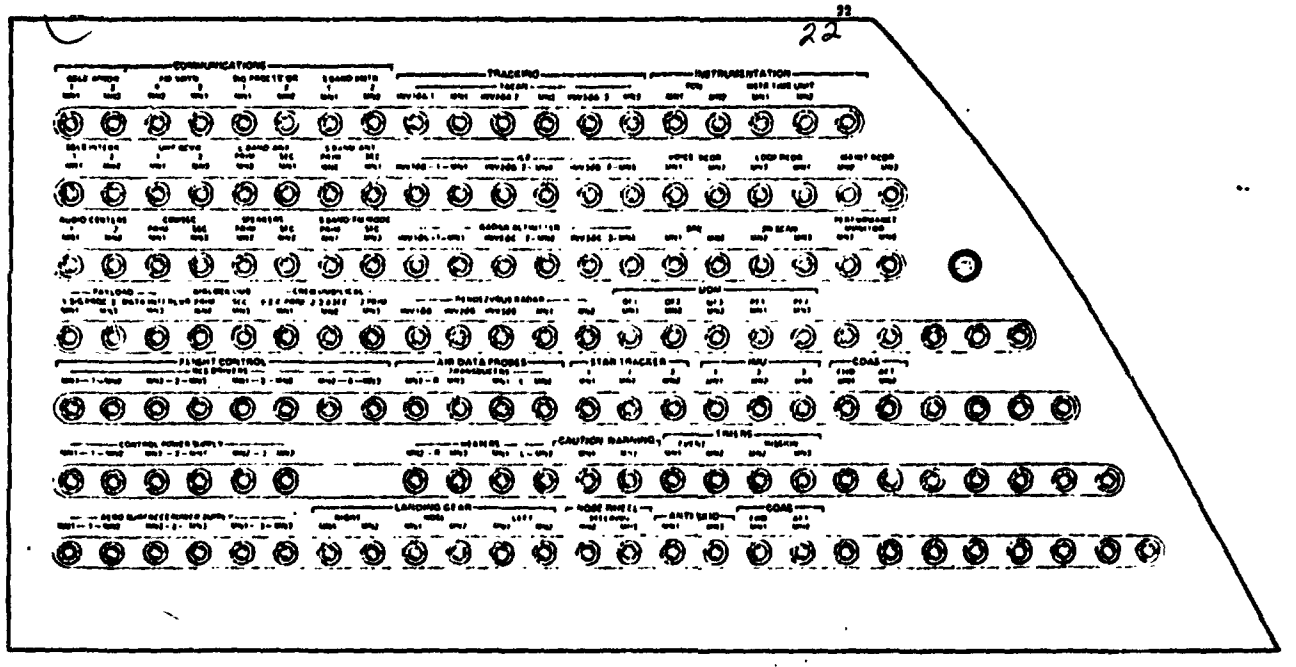
APU READY
CONTROL PWR


22
COMMUNICATIONS
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FLIGHT CONTROL
AIR DATA PROBES
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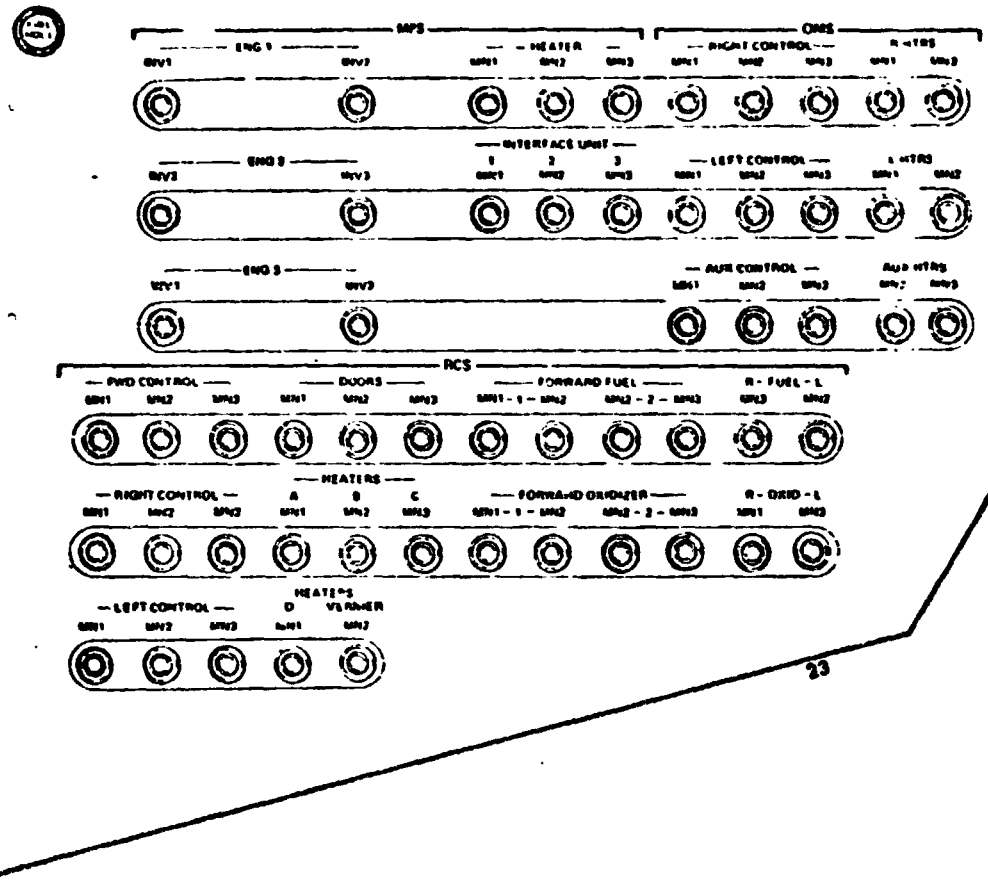
CDAS
CAUTION WARNING
LANDING GEAR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HEATER
ENG 2
INTERFACE UNIT
1
2
3
ENG 3
OMS
RIGHT CONTROL
LEFT CONTROL
AUX CONTROL
RCS
RCS CONTROL
DOORS
FORWARD FUEL
R - FUEL - L
HEATERS
A
B
C
FORWARD OXIDIZER
R - OXID - L
HEATERS
D
VERNIER
23

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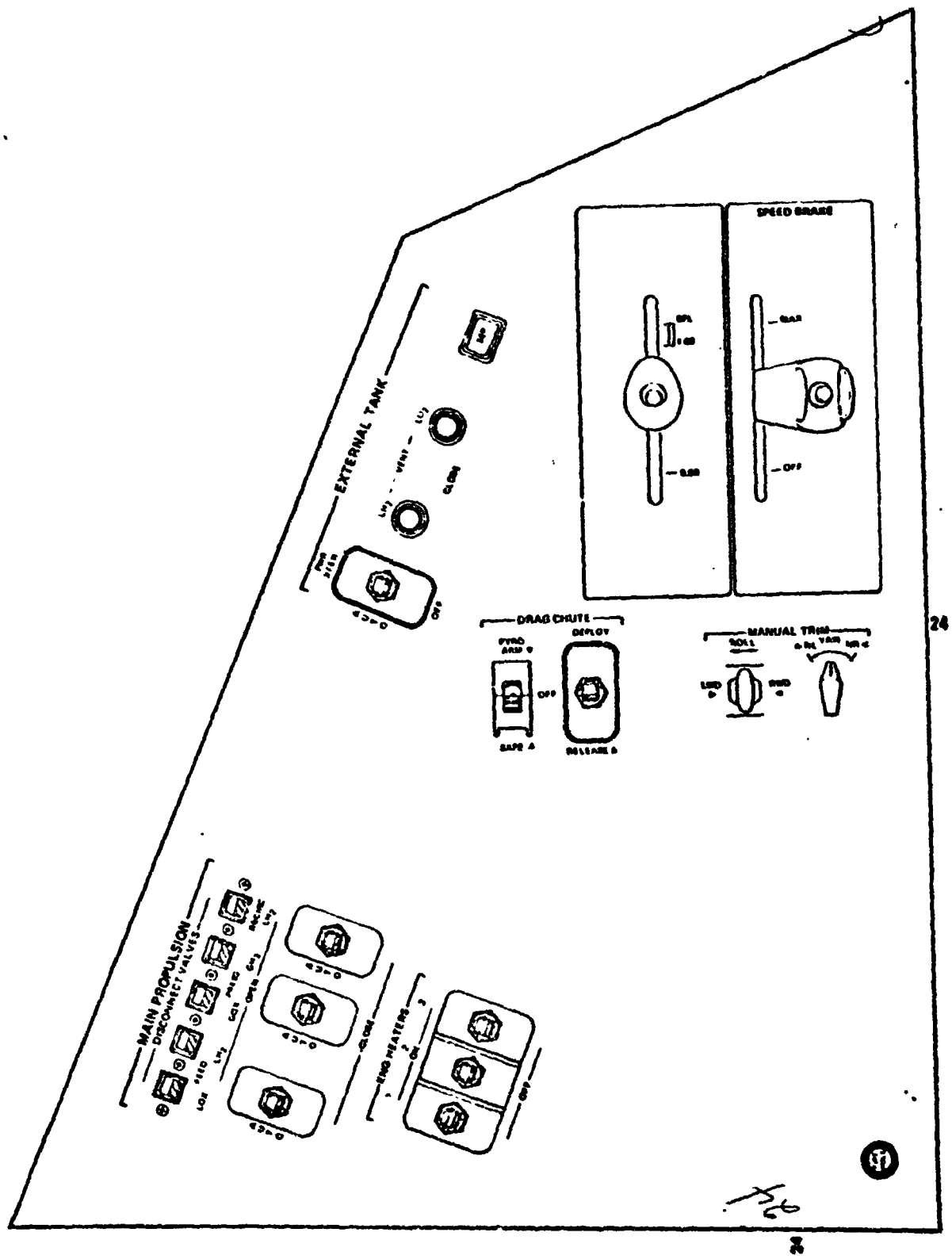

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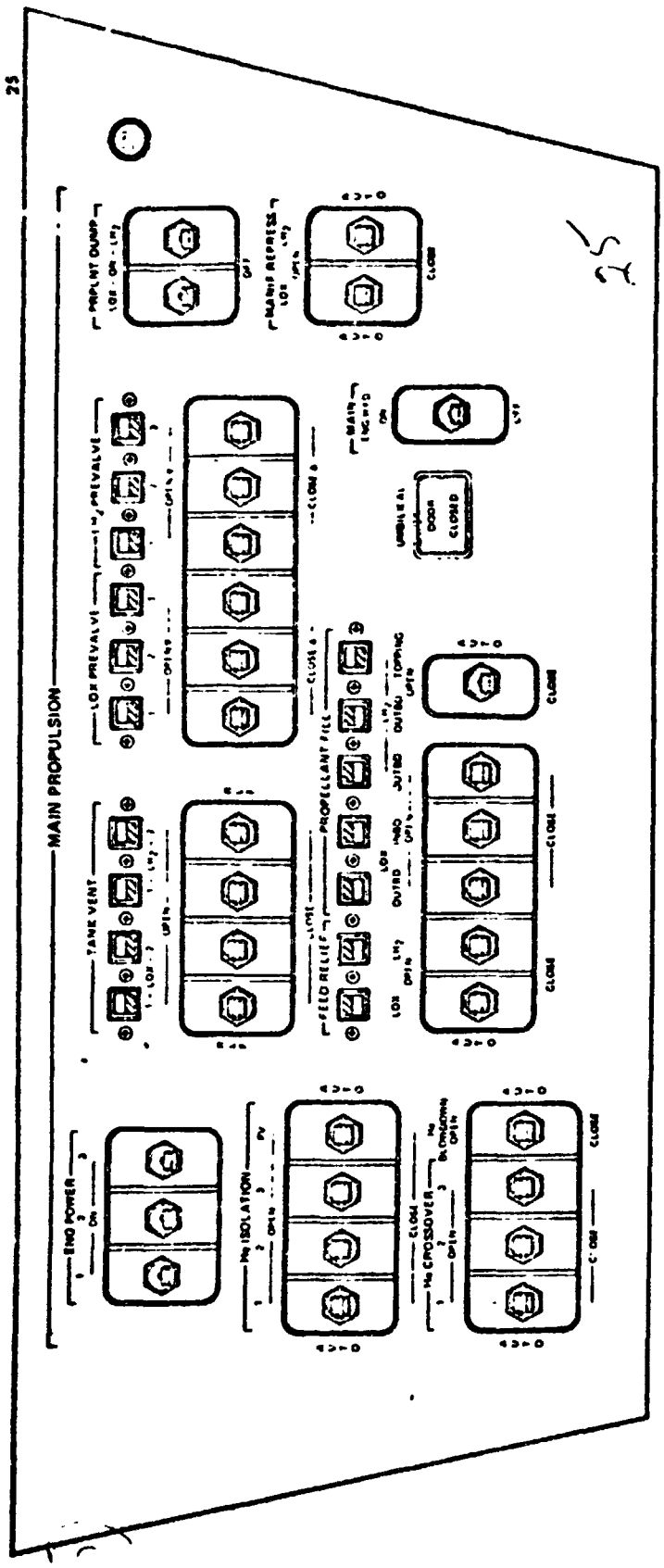

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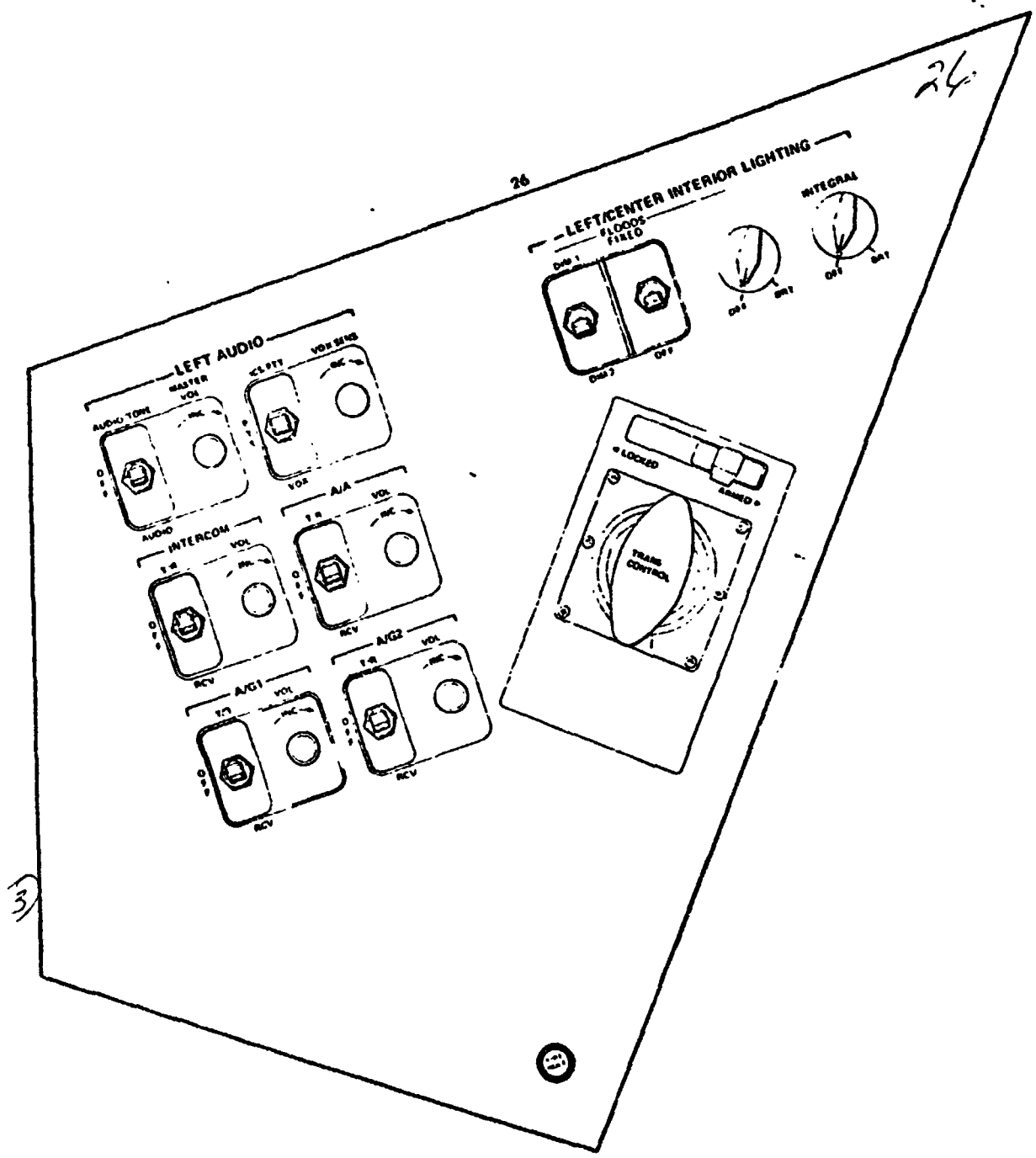

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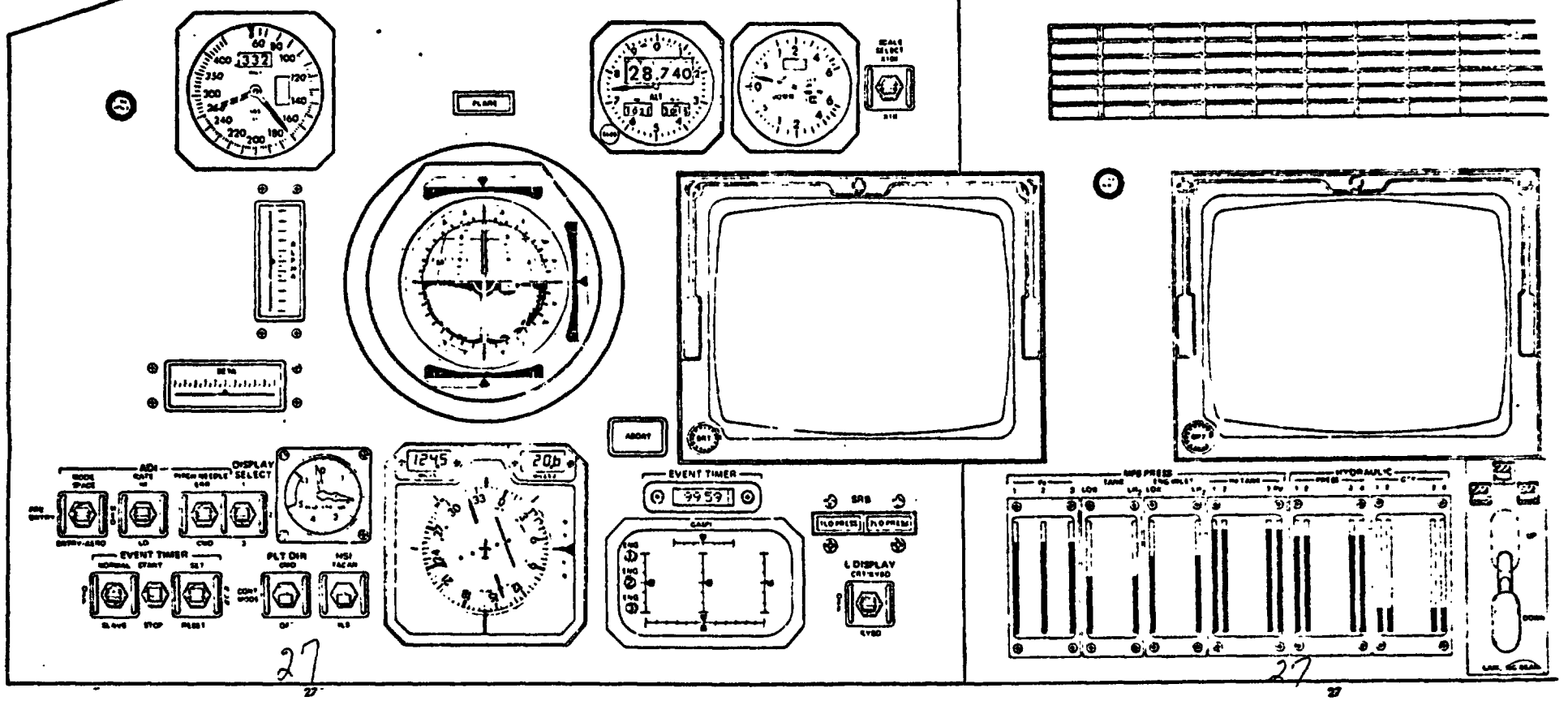
CAUTION/WARNING



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DATE 6/22/73	SINGER-GENERAL PRECISION, INC. LINK DIVISION BINGHAMTON, NEW YORK	PAGE NO. A-30
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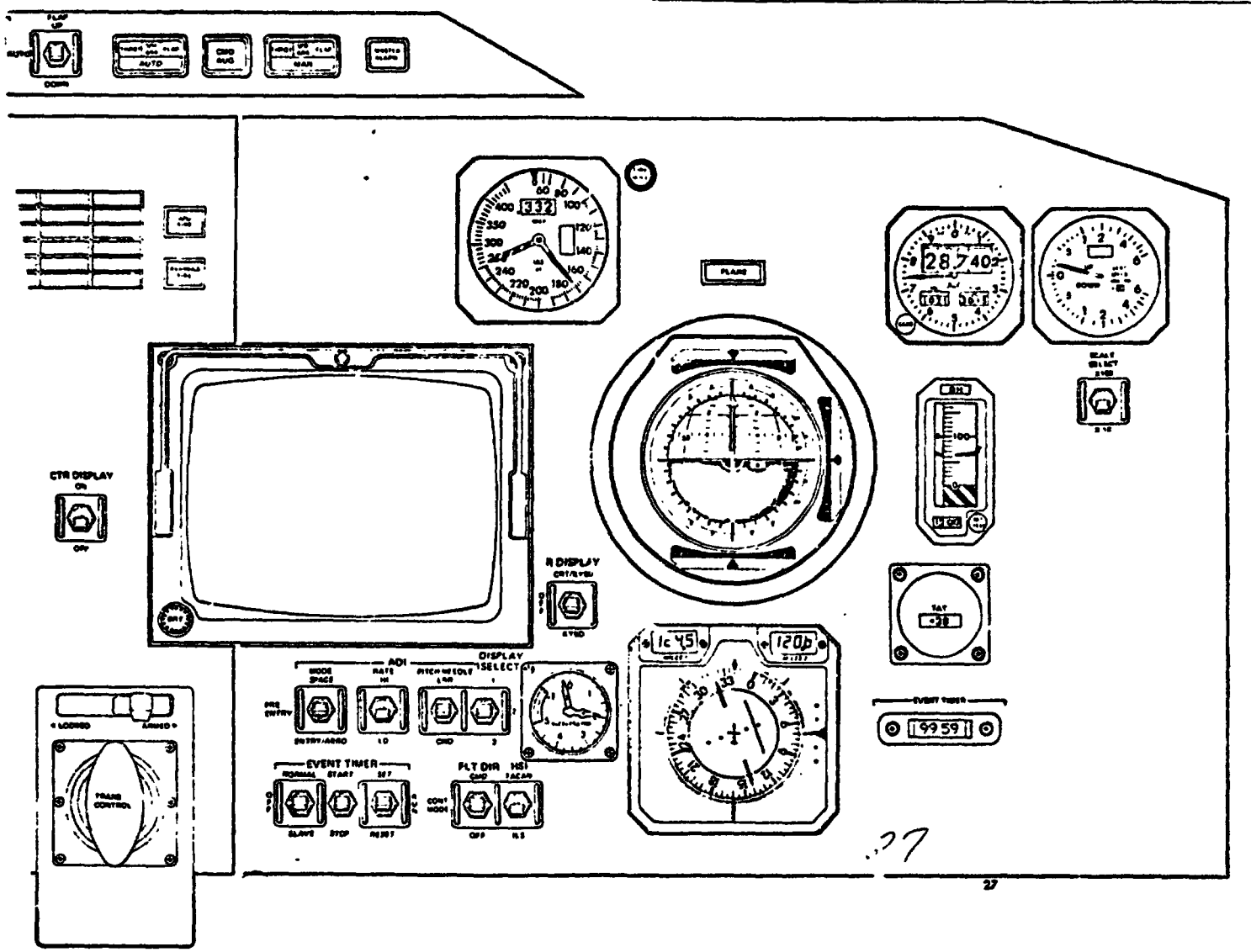

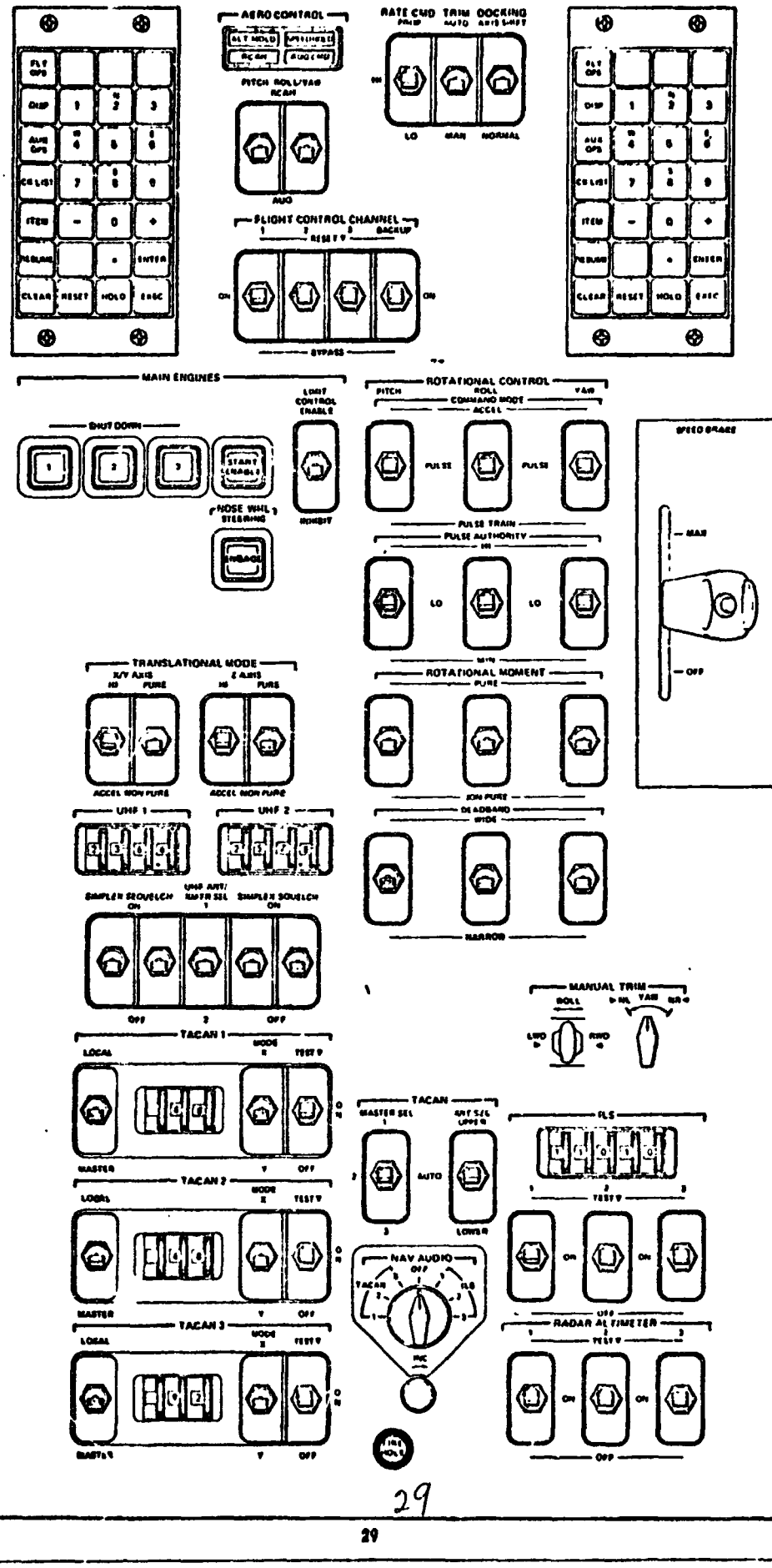

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REV. A 11/30/73
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LINK DIVISION
BINGHAMTON, NEW YORK
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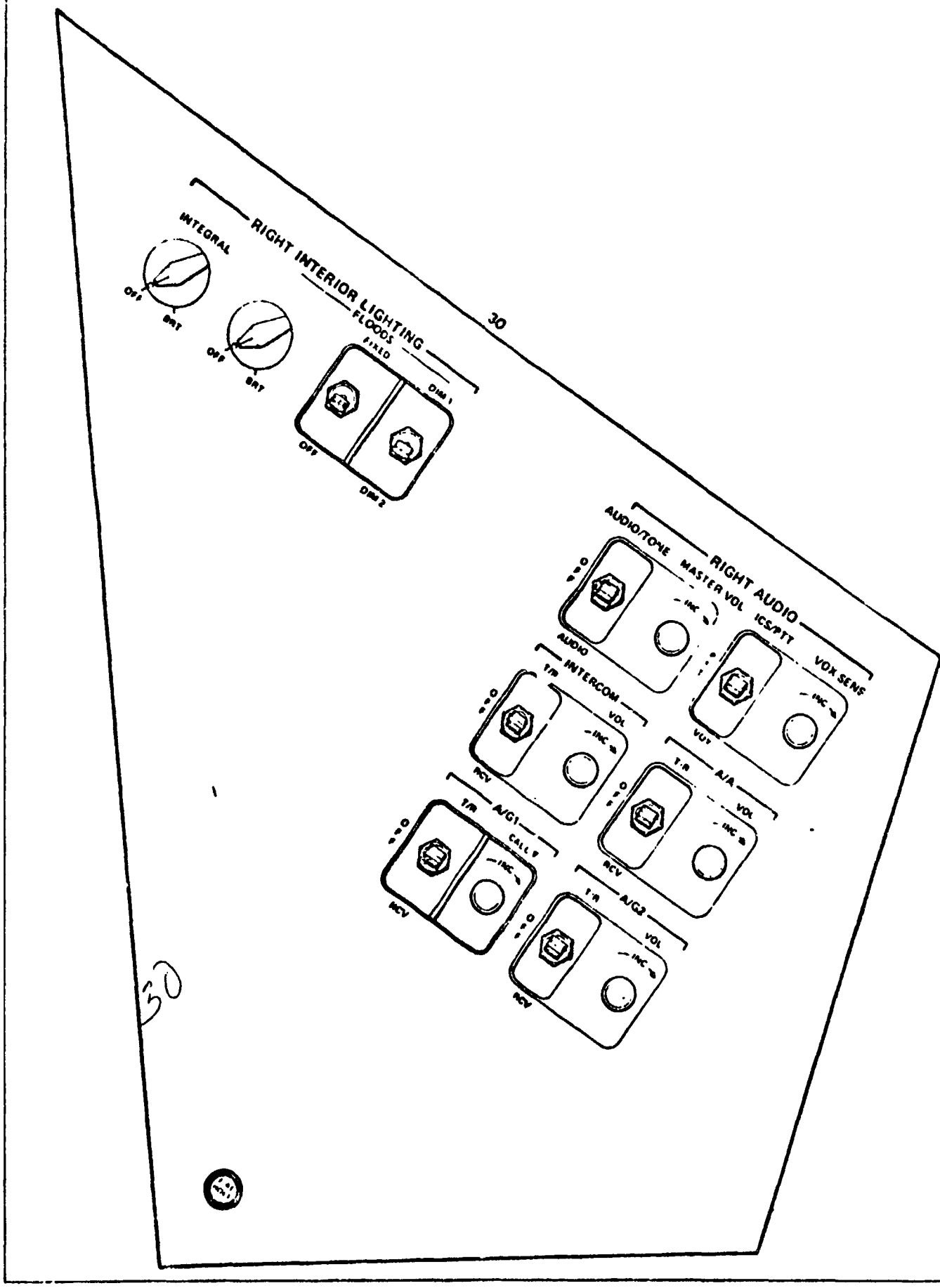
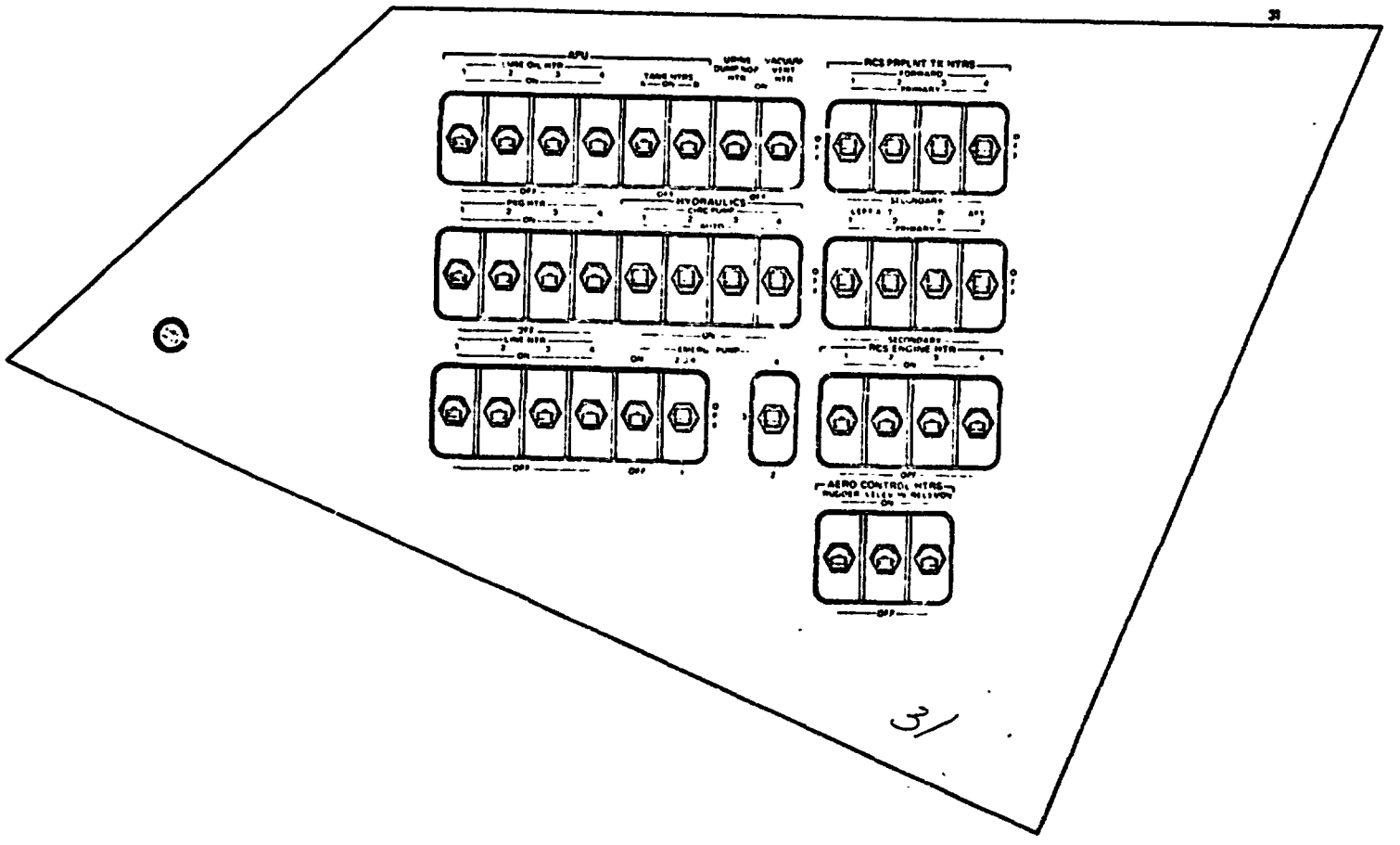
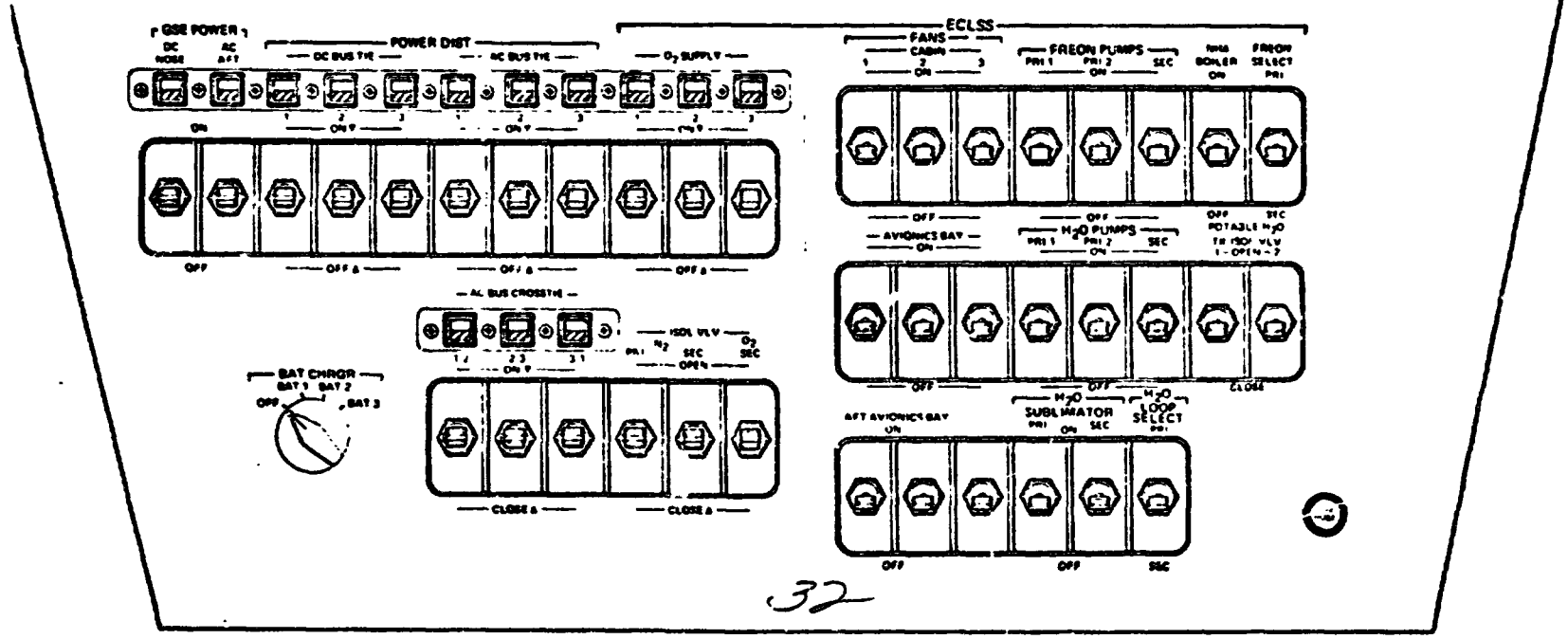

RIGHT INTERIOR LIGHTING
INTEGRAL
OFF
BRT
OFF
BRT
FLOODS
FIELD
DIM 1
OFF
DIM 2
30
RIGHT AUDIO
AUDIO/TONE
MASTER VOL
INC
ICS/PTT
VOX SENS
AUDIO
INTERCOM
T/R
VOL
INC
RCV
VOX
T/R
A/A
VOL
INC
RCV
T/R
A/G1
CALL
INC
RCV
T/R
A/G2
VOL
INC
RCV
30

F-398-8-A


APU
RCS PRPLNT TK HTRS
FORWARD
PRIMARY
HYDRAULICS
SECONDARY
RCS ENGINE HTR
AERO CONTROL HTRS
OFF

32


GSE POWER
DC NOSE
AC AFT
POWER DIST
DC BUS TIE
AC BUS TIE
O2 SUPPLY
ECLSS
FANS
CABIN
FREON PUMPS
PRI 1
PRI 2
SEC
WMA BOILER
FREON SELECT
AVIONICS BAY
H2O PUMPS
POTABLE H2O
AC BUS CROSSTIE
ISOL VLV
BAT CHRGR
BAT 1
BAT 2
BAT 3
H2O SUBLIMATOR
H2O LOOP SELECT
AFT AVIONICS BAY
CLOSE

32

DATE 6/22/73	THE SINGER COMPANY SIMULATION PRODUCTS DIVISION	PAGE NO. A-33
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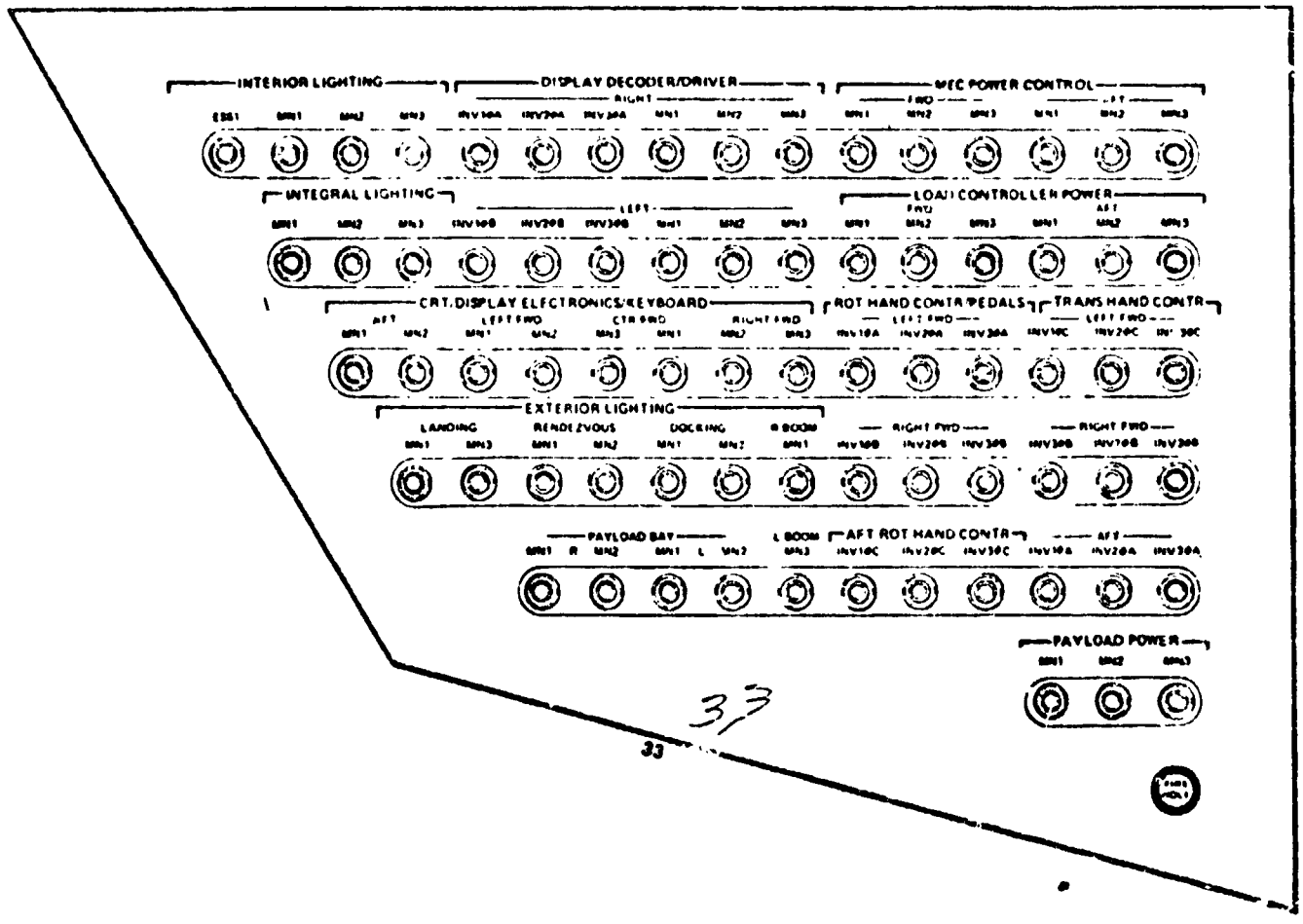
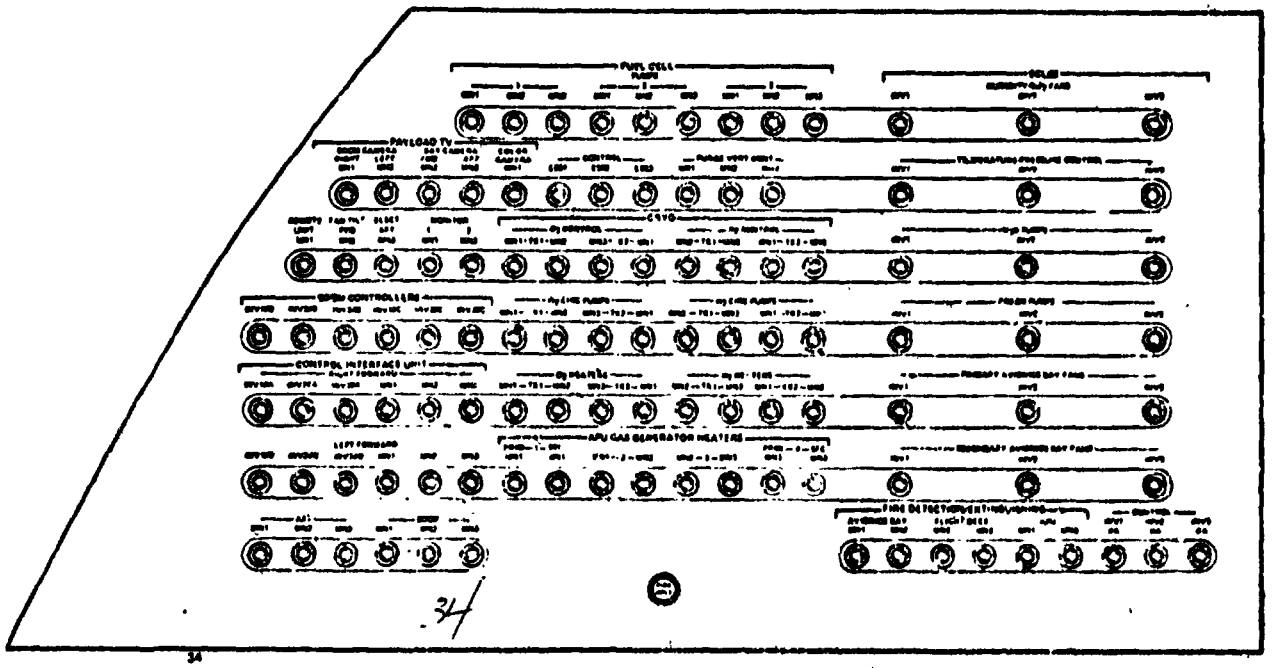


F-398-8-A


FUEL CELL PURGE
SOLID
PAYLOAD TV
CRYO
APU GAS GENERATOR HEATERS
34

TBD

RUDDER PEDALS

DATE 6/22/73	THE SINGER COMPANY SIMULATION PRODUCTS DIVISION	PAGE NO. A-38
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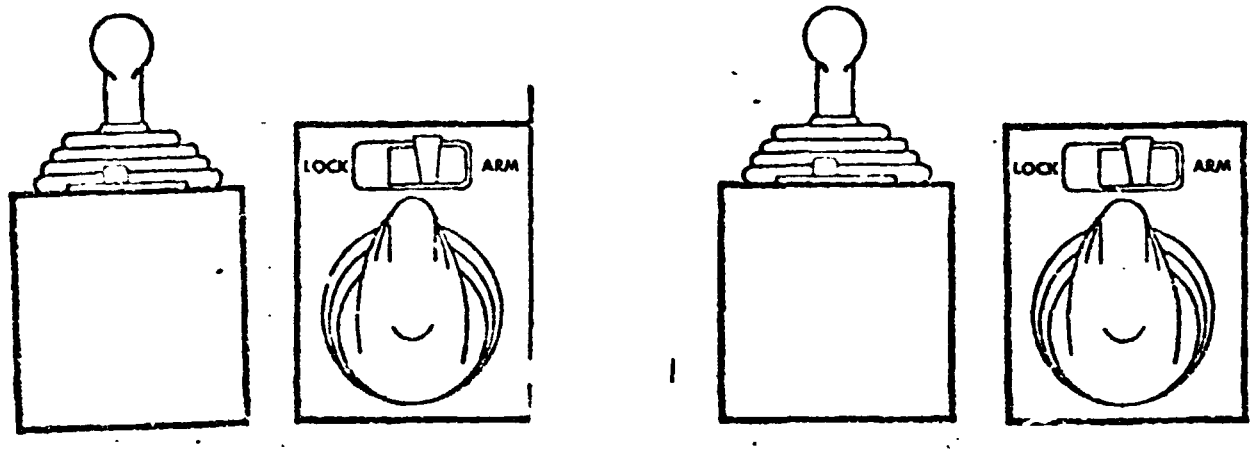


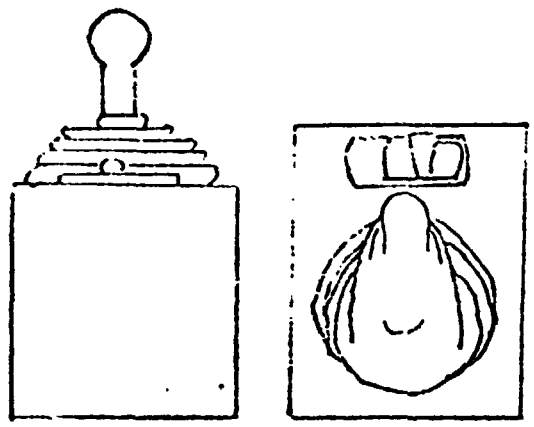
COMMANDER

PILOT

TRANSLATIONAL HAND CONTROL

ROTATIONAL HAND CONTROL

PARKING BRAKE



MANIPULATOR STATION

TRANSLATIONAL HAND CONTROL

ROTATIONAL HAND CONTROL

MANIPULATOR CONTROLS (TBD)

DATE 6-22-73	THE SINGER COMPANY SIMULATION PRODUCTS DIVISION	PAGE NO.
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SMS BASELINE DEFINITION REPORT

ADDENDUM B

SMS CONTROL AND DISPLAY

ELECTRICAL SCHEMATIC DIAGRAMS

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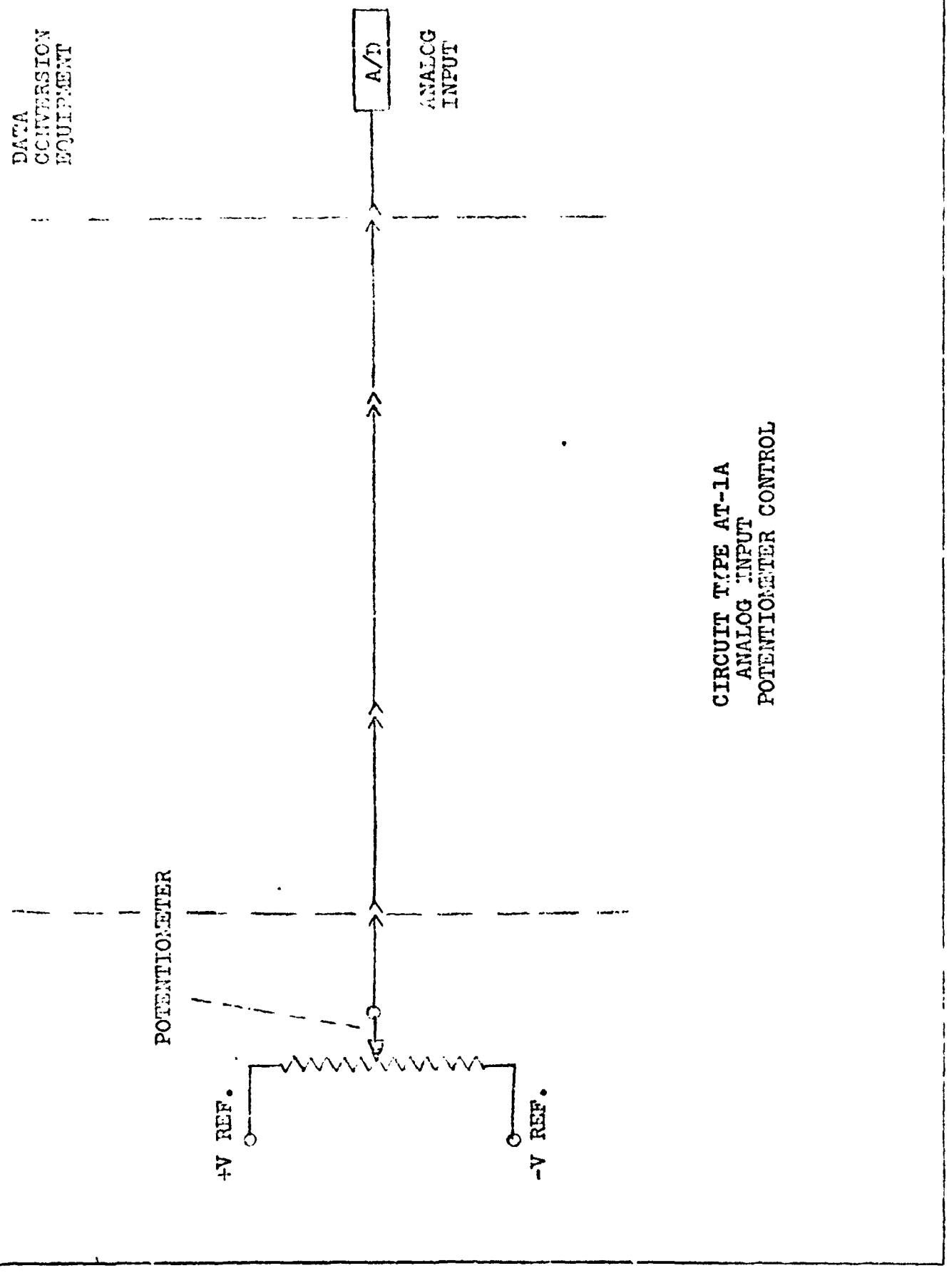

CIRCUIT TYPE AT-1A
ANALOG INPUT
POTENTIOMETER CONTROL

F-399-8-A

DATE 6-22-73	THE SINGER COMPANY SIMULATION PRODUCTS DIVISION BINGHAMTON, NEW YORK	PAGE NO. B-2
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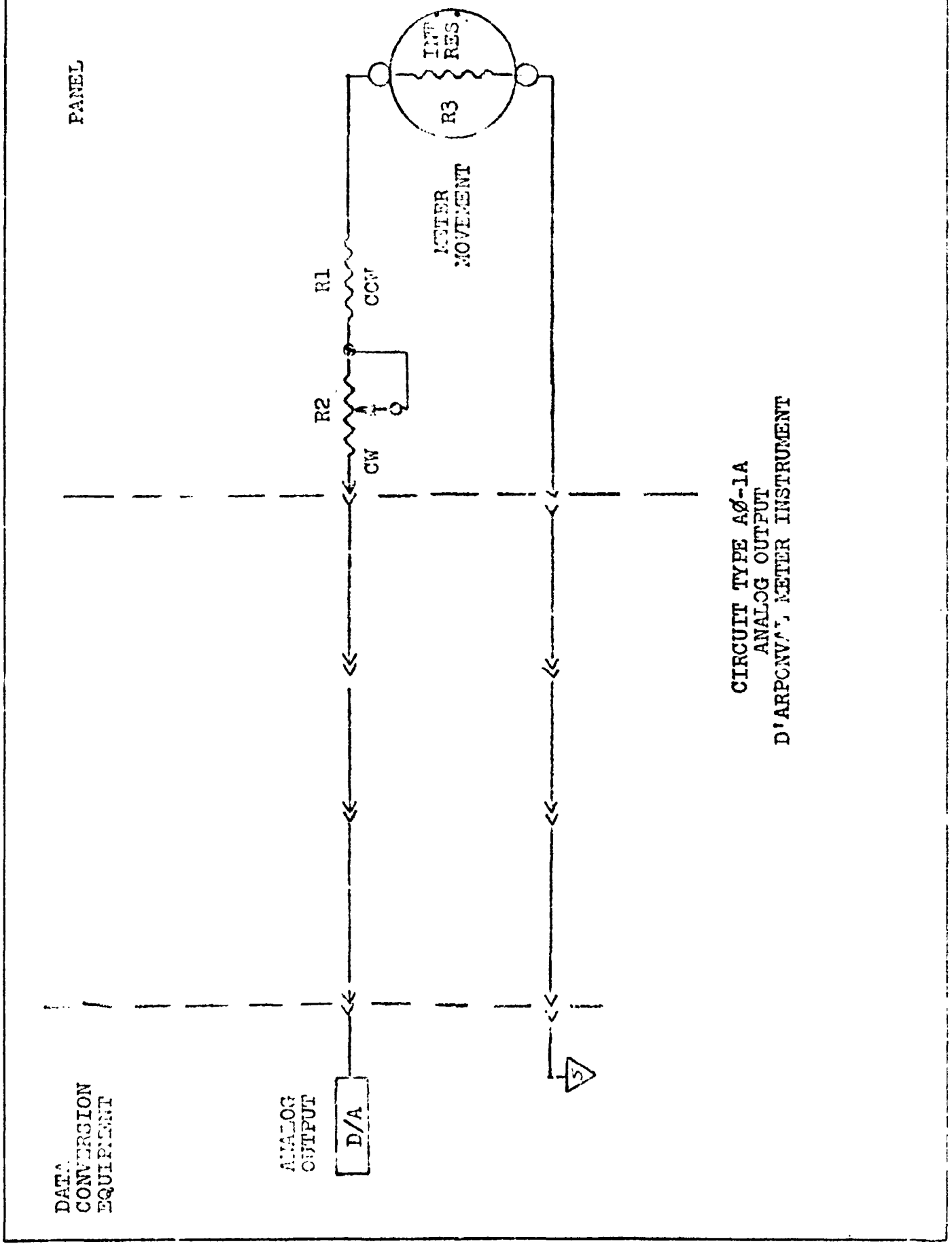


F-398.8.4

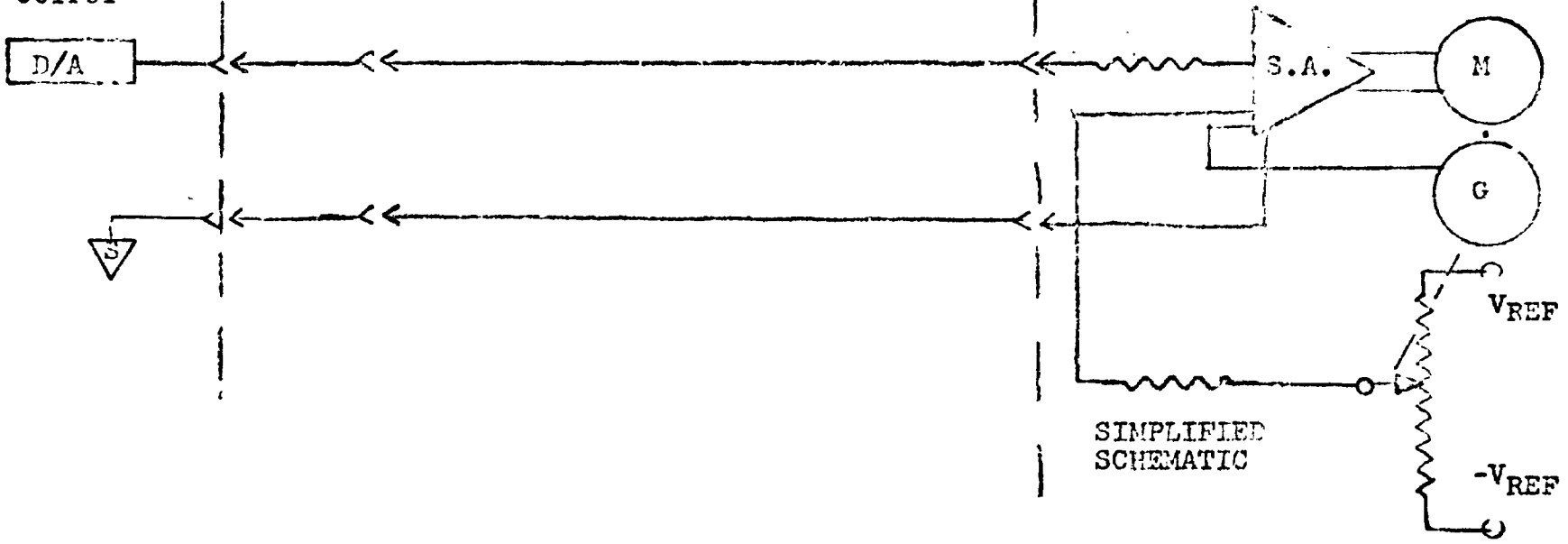
F-398-8-A

DATA
CONVERSION
EQUIPMENT

ANALOG
OUTPUT

D/A

2



SIMPLIFIED
SCHEMATIC

CIRCUIT TYPE AØ-1B
ANALOG OUTPUT
D.C. SERVO INSTRUMENT OR DEVICE

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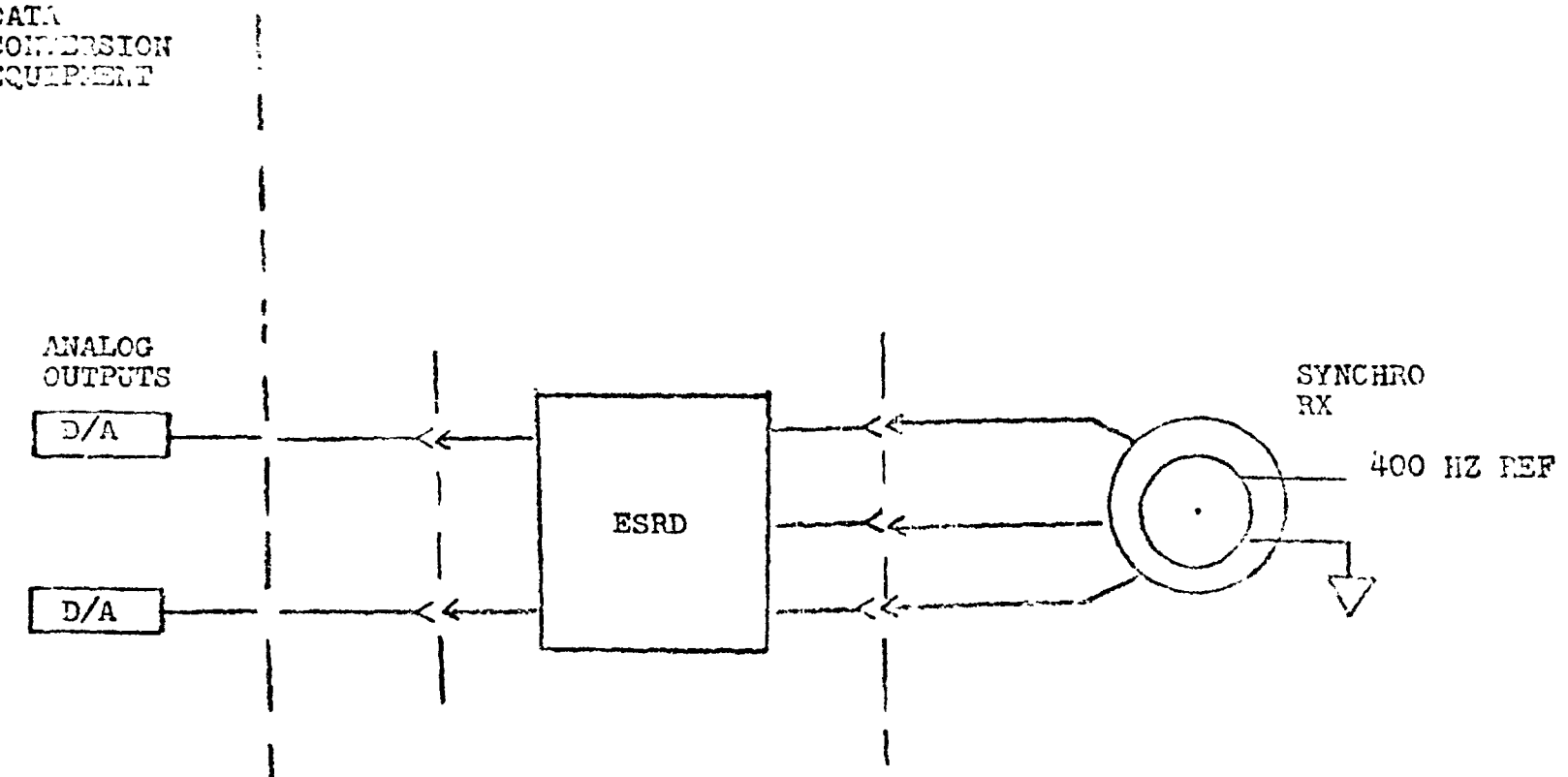

CIRCUIT TYPE AØ-2A
ANALOG OUTPUT
SYNCHRO RX.

DATE 6-22-73
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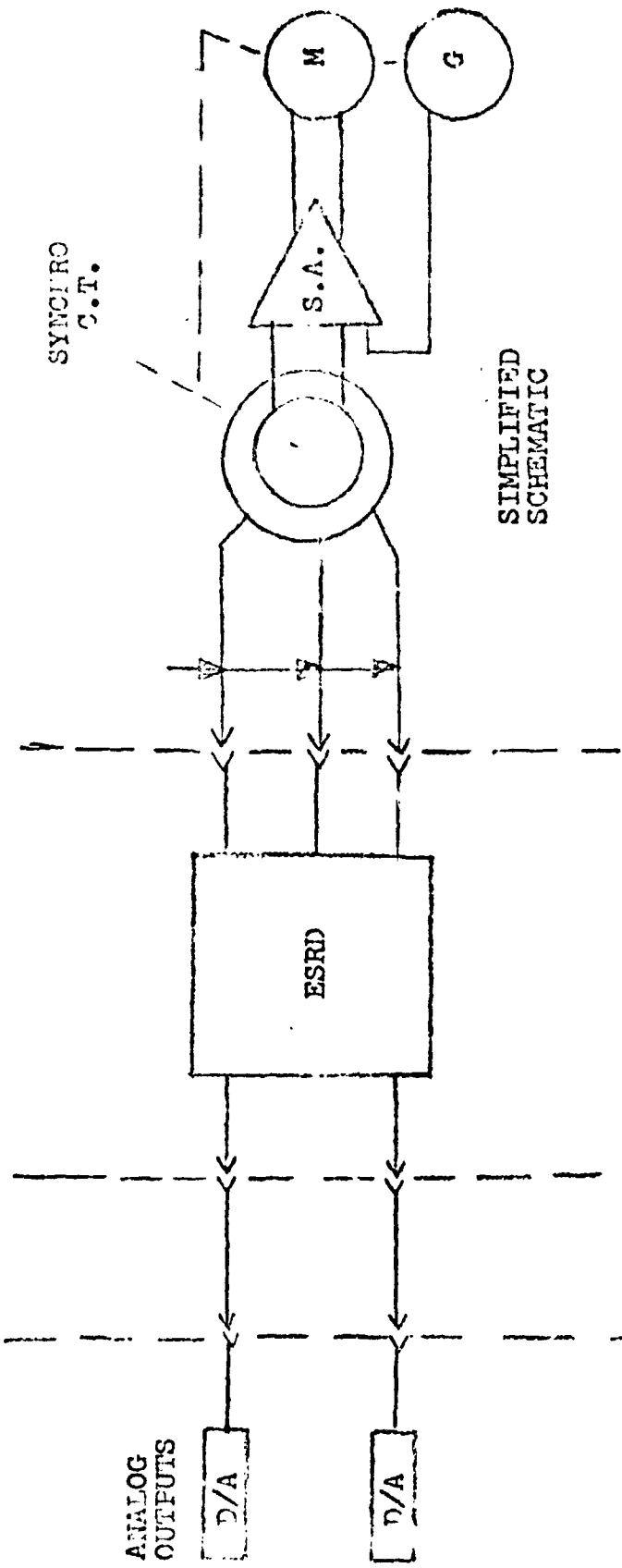
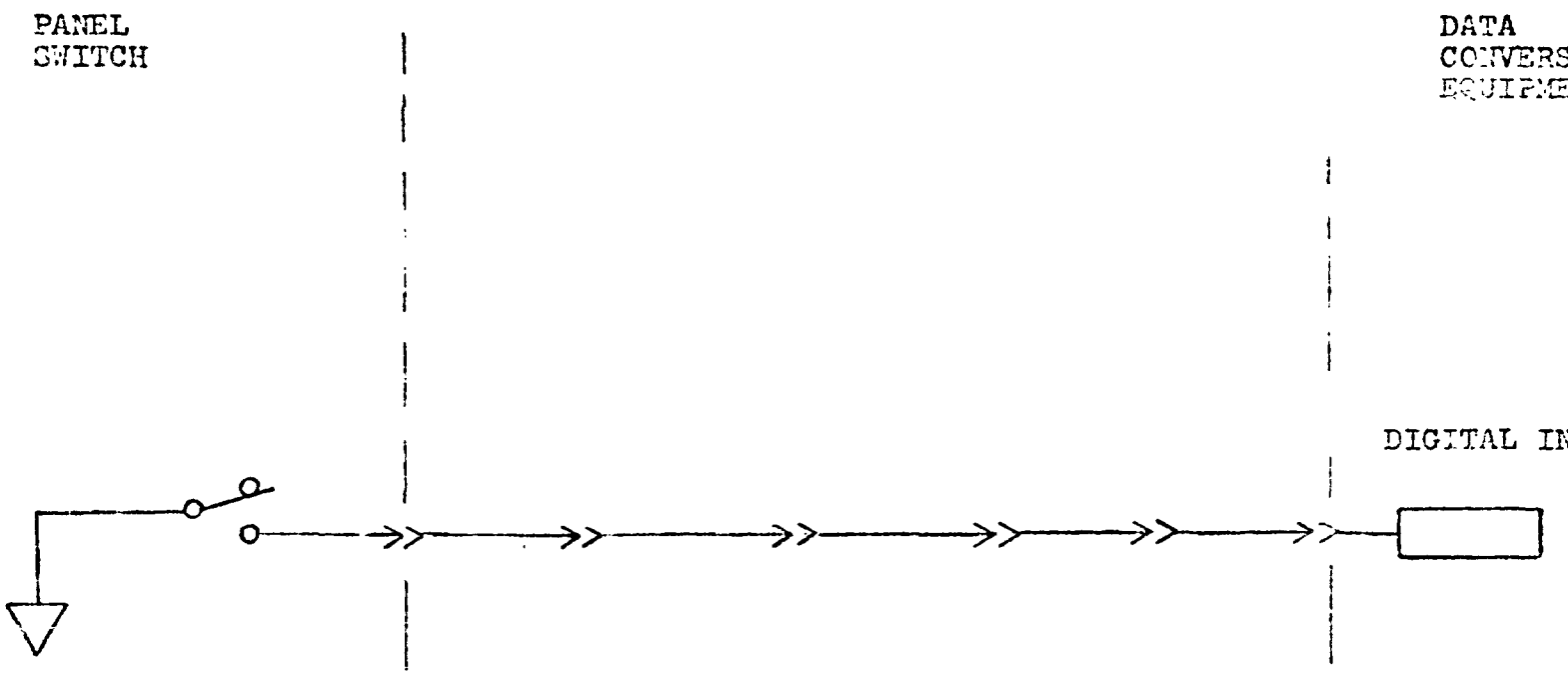


SIMPLIFIED
SCHEMATIC

CIRCUIT TYPE AØ-2B
ANALOG OUTPUT
A.C. SERVO INSTRUMENT WITH C.T. FOLLOW-UP

F-398-8

F-398-9-A



CIRCUIT TYPE DI-1A
TWO POSITION ALTERNATE ACTION TOGGLE SWITCH

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REV.

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BINGHAMTON, NEW YORK

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DATE 6-22-73	THE SINGER COMPANY SIMULATION PRODUCTS DIVISION	PAGE NO. B-7
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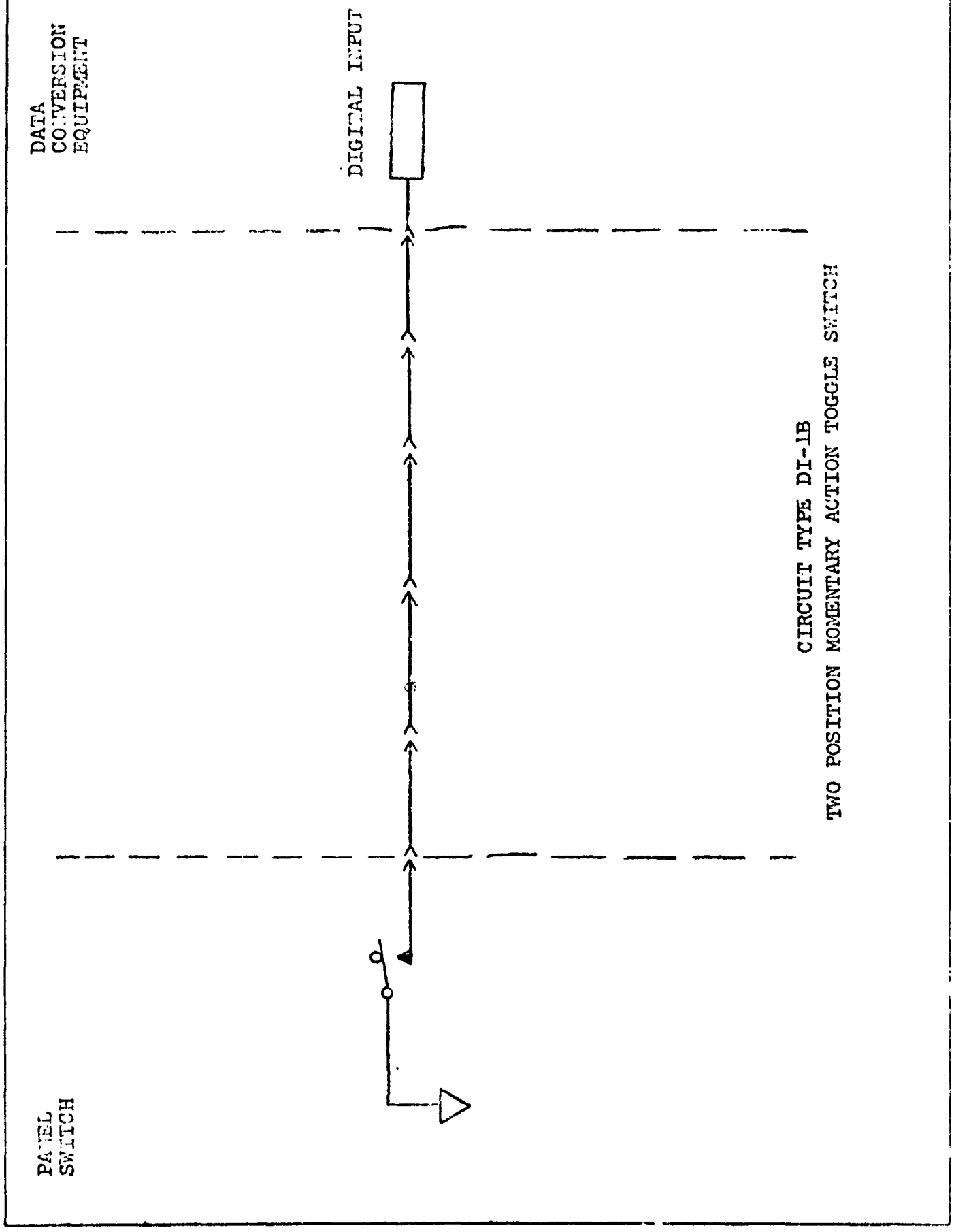
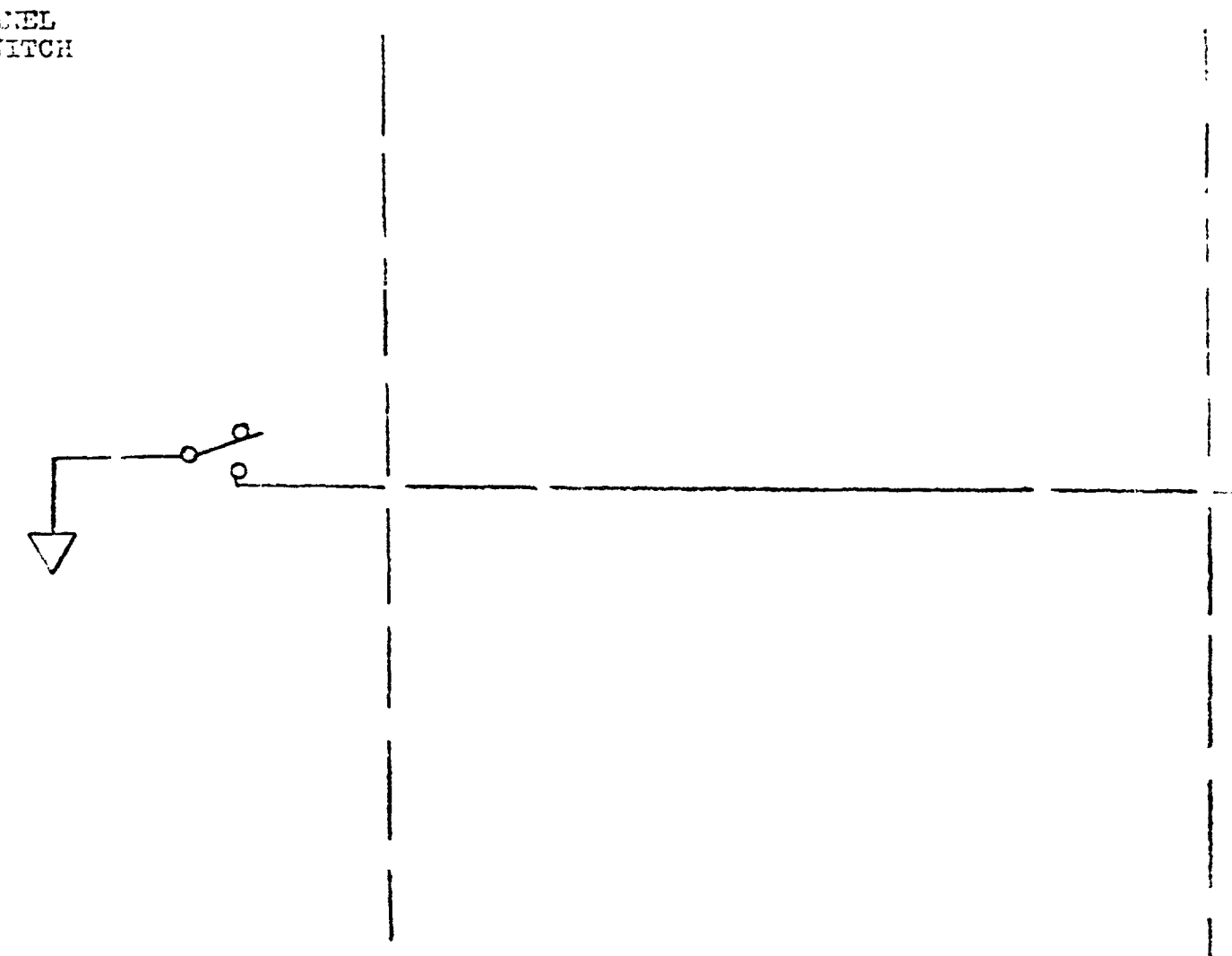


F-398-8-A

F-398-8-A



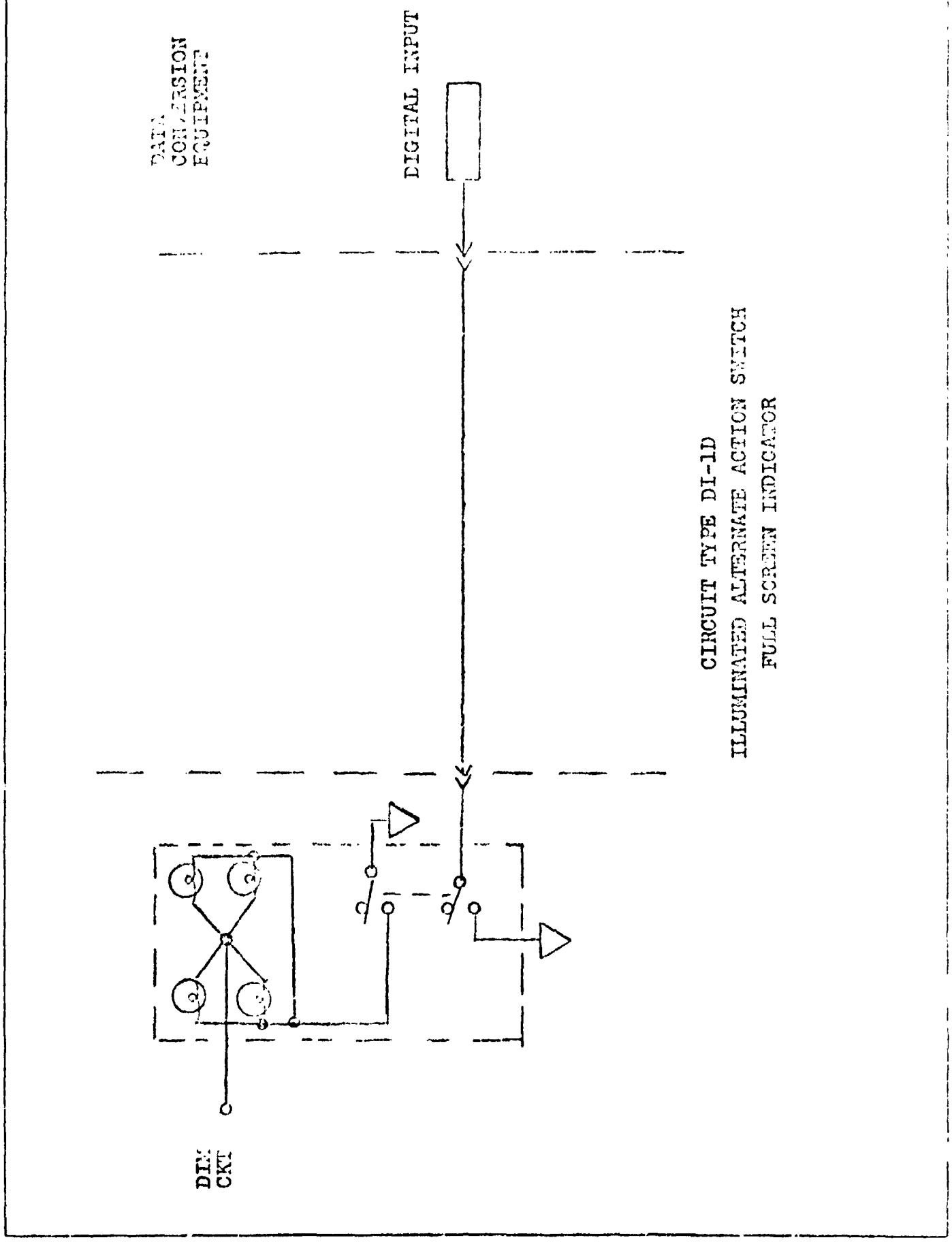
CIRCUIT TYPE DI-1C

LARGE TWO POSITION ALTERNATE ACTION TOGGLE SWITCH

DATE 6-22-73
REV.

THE SINGER COMPANY
SIMULATION PRODUCTS DIVISION
BINGHAMTON, NEW YORK

PAGE NO. B-8
REP. NO.


DATA
CONVERSION
EQUIPMENT
DIGITAL INPUT
DI
CKT
CIRCUIT TYPE DI-1D
ILLUMINATED ALTERNATE ACTION SWITCH
FULL SCREEN INDICATOR

DATE 6-22-73	THE SINGER COMPANY SIMULATION PRODUCTS DIVISION	PAGE NO. B-10
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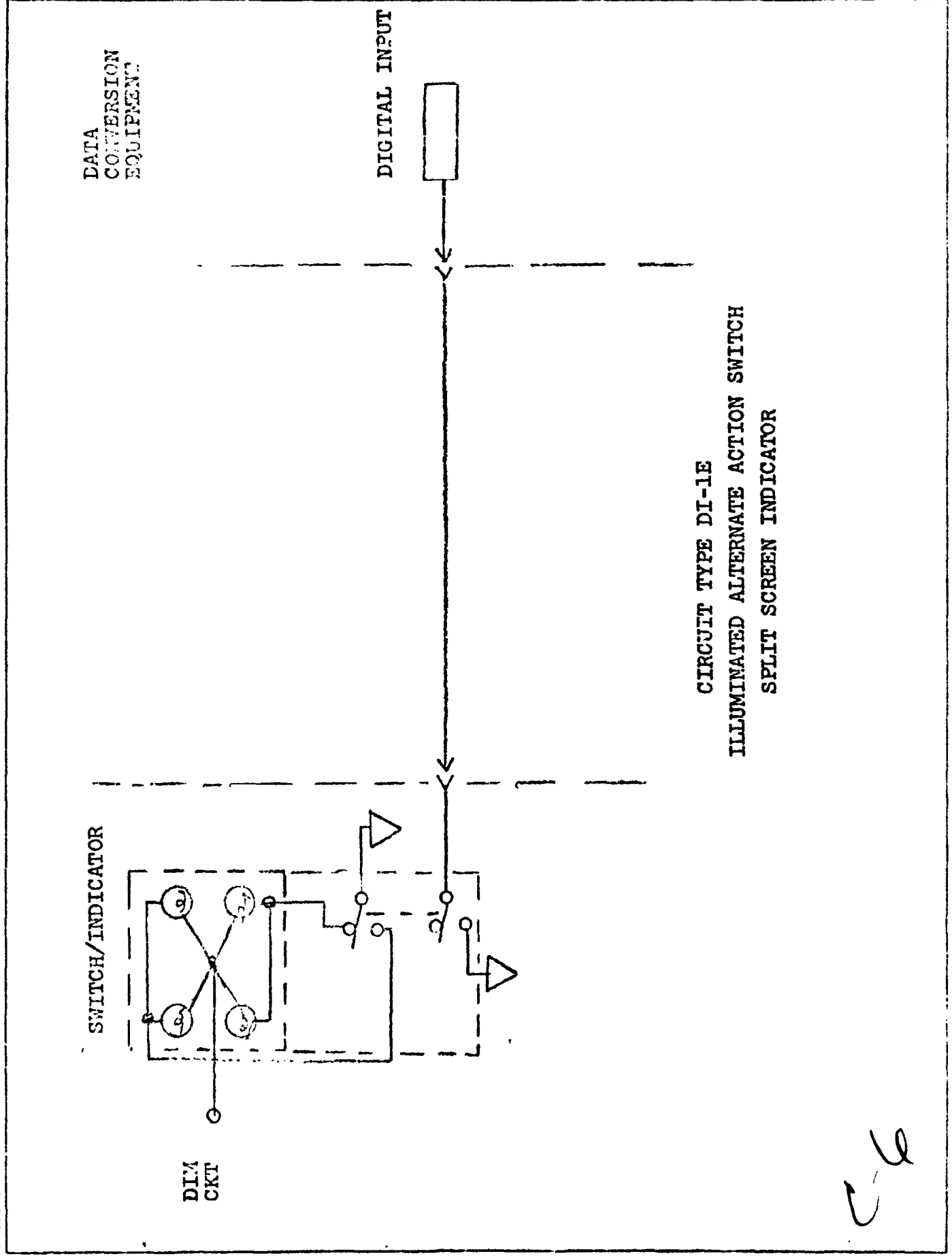
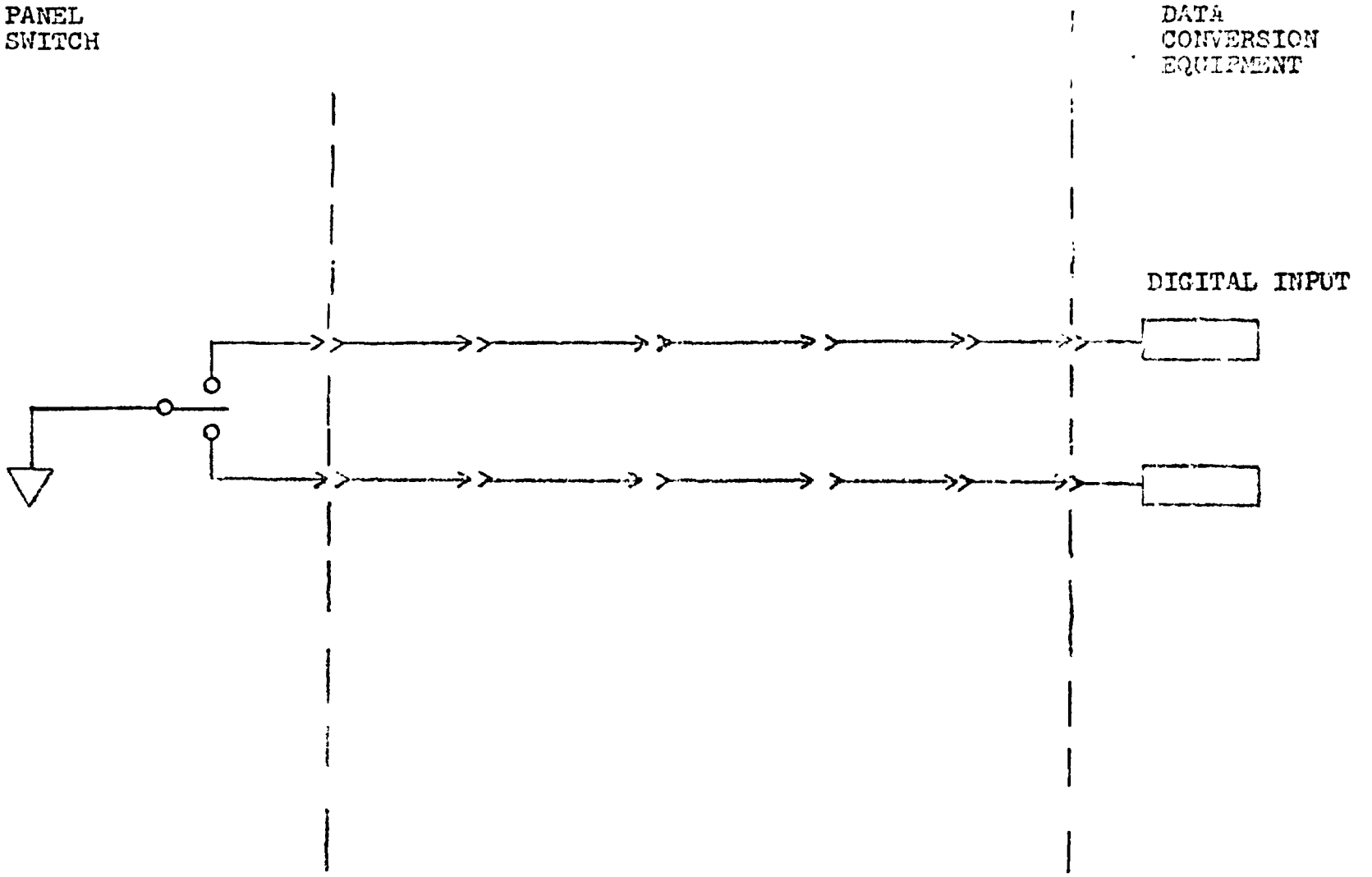


CIRCUIT TYPE DI-1E
ILLUMINATED ALTERNATE ACTION SWITCH
SPLIT SCREEN INDICATOR

F-398-3-A

F-398-8-A



CIRCUIT TYPE DI-2A

THREE POSITION ALTERNATE ACTION TOGGLE SWITCH

DATE 6-22-73

REV

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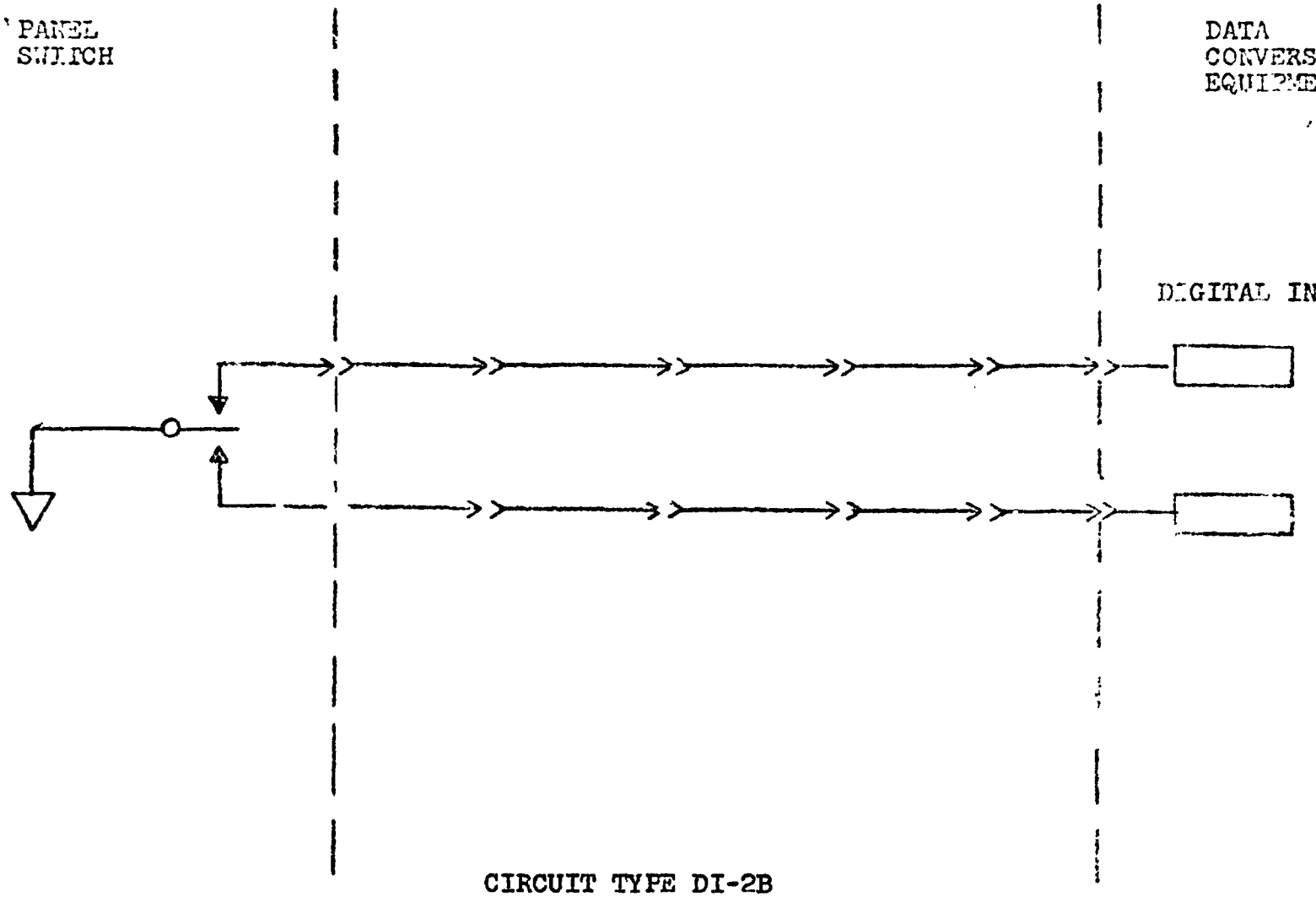
F-398-8-A



CIRCUIT TYPE DI-2B

THREE POSITION (CENTER NORMAL) MOMENTARY TOGGLE SWITCH

DATE 6-22-73

REV.

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SIMULATION PRODUCTS DIVISION
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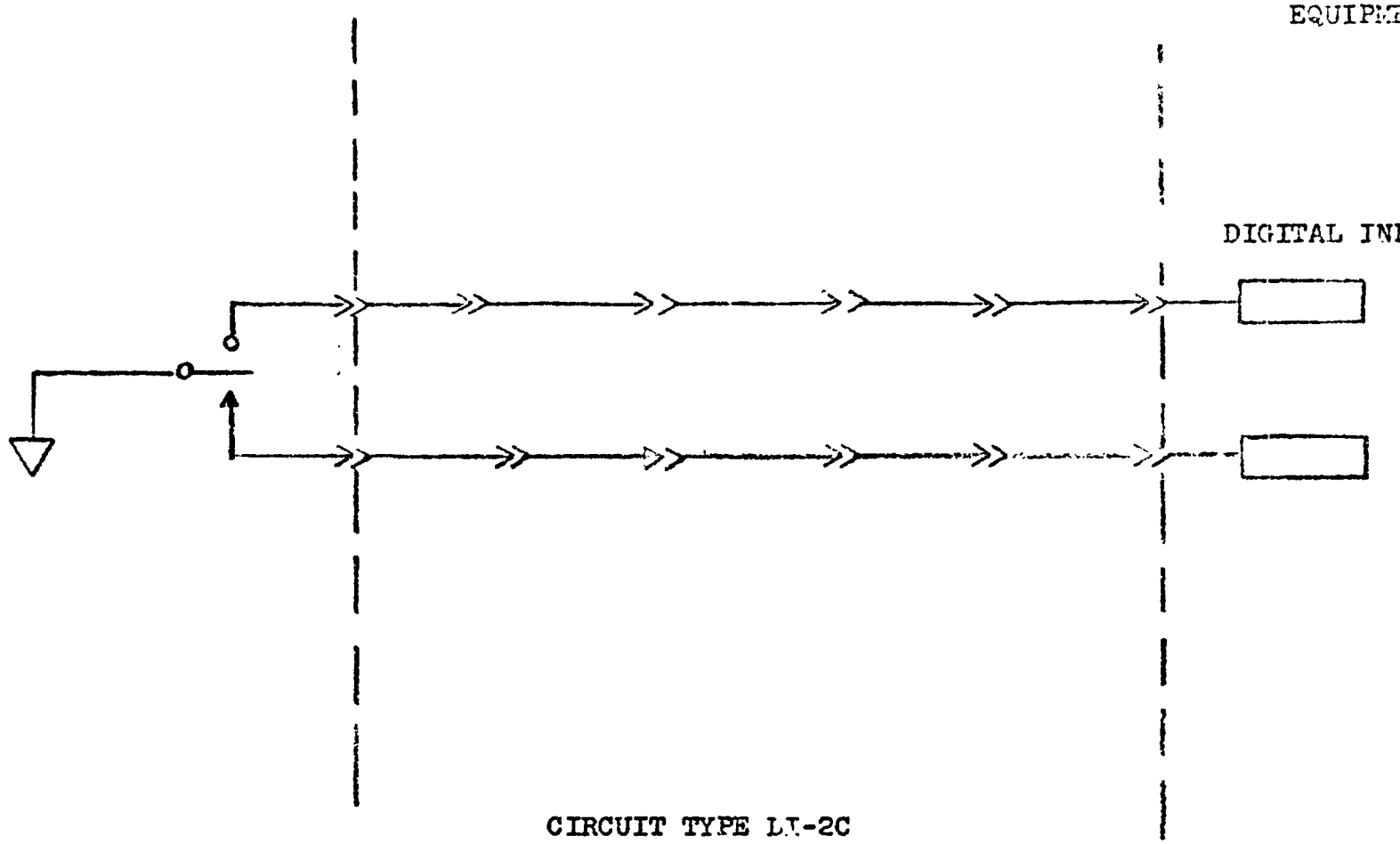
F-398-8-A



CIRCUIT TYPE LI-2C

THREE POSITION (CENTER NORMAL) COMBINATION ALTERNATE ACTION/MOMENTARY TOGGLE SWITCH

DATE 6-22-62

REV.

THE SINGER COMPANY
SIMULATION PRODUCTS DIVISION
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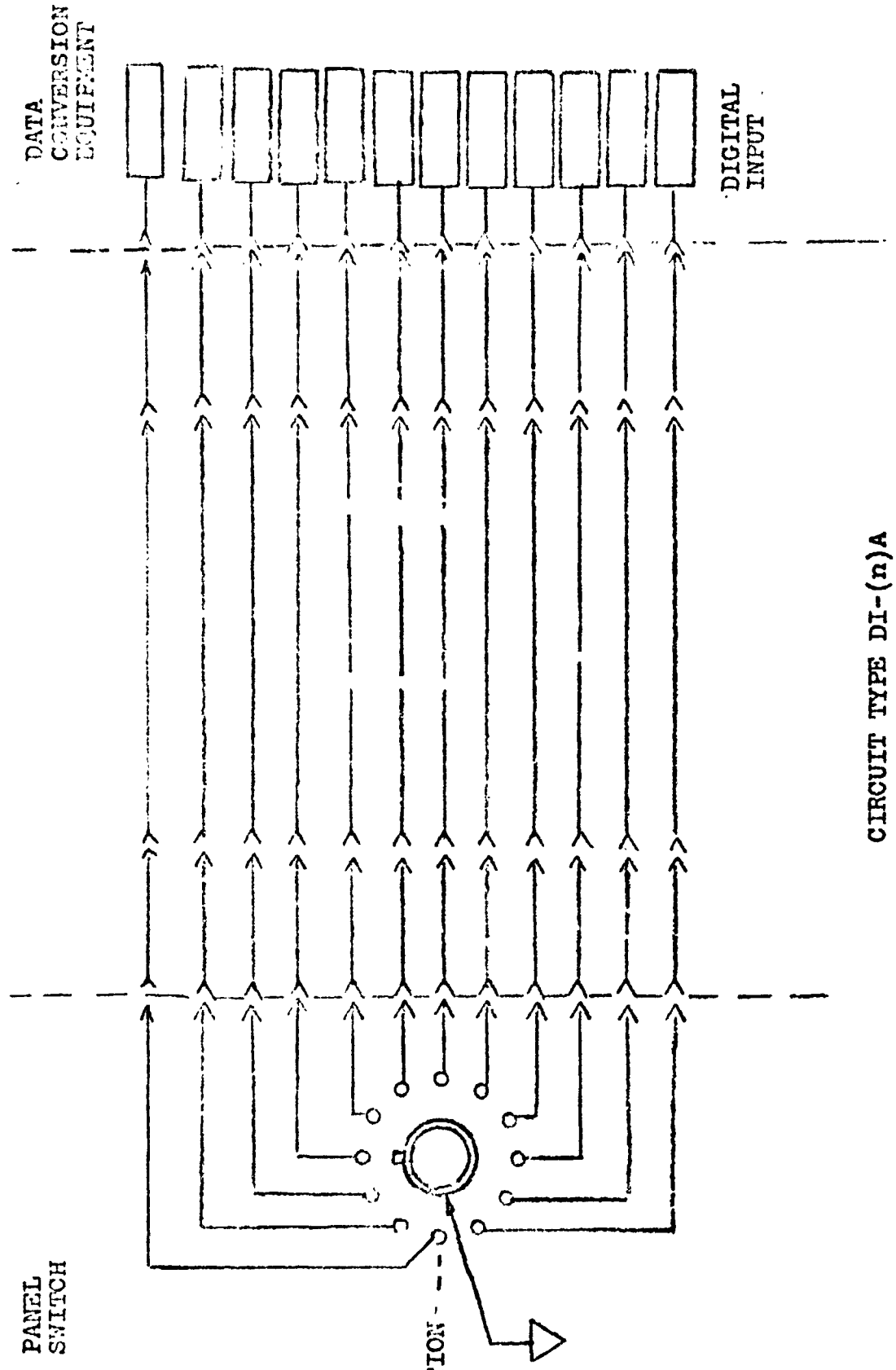
REP. NO.



CIRCUIT TYPE DI-(n)A

ROTARY SWITCH

* SPECIFY NUMBER OF POSITIONS (n) AND NUMBER OF DI BITS

F-398-8-A

DATE 6-22-73	THE SINGER COMPANY SIMULATION PRODUCTS DIVISION BINGHAMTON, NEW YORK	PAGE NO. B-15
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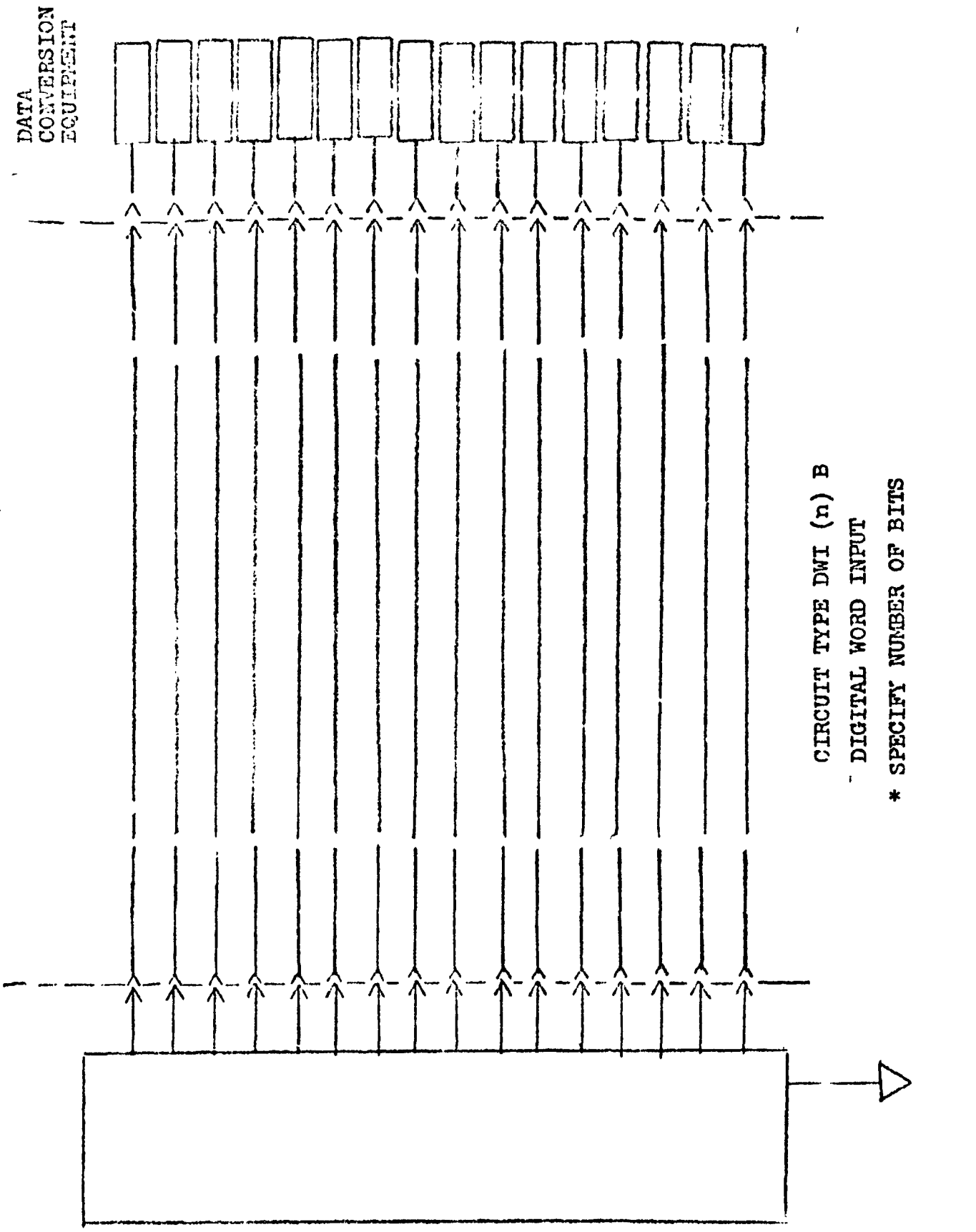
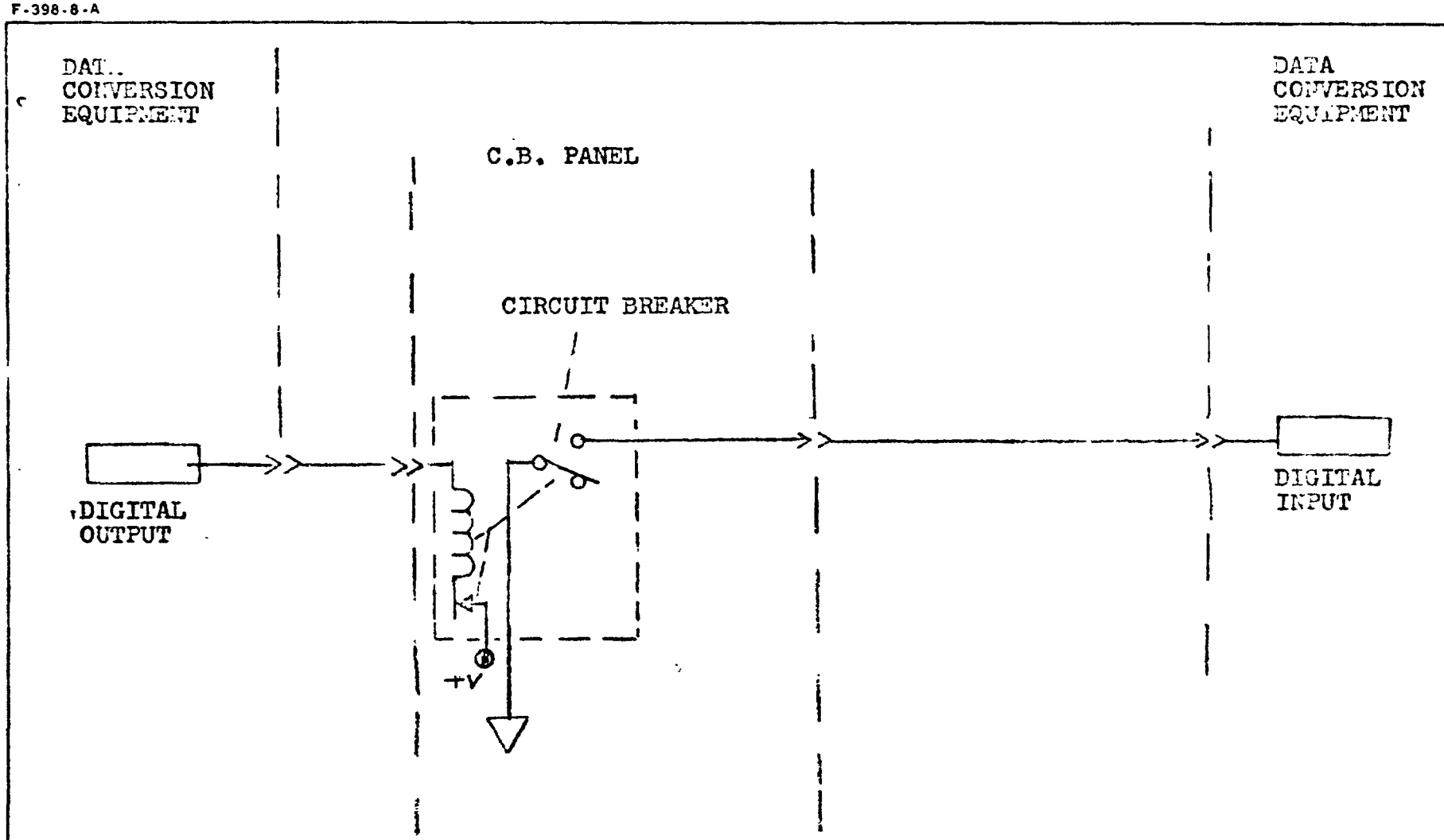


F.398.8.A

F-398-8-A



CIRCUIT TYPE DIØ-1A
POPABLE CIRCUIT BREAKER

DATE 6-22-73
REV.

THE SINGER COMPANY
SIMULATION PRODUCTS DIVISION
BINGHAMTON, NEW YORK

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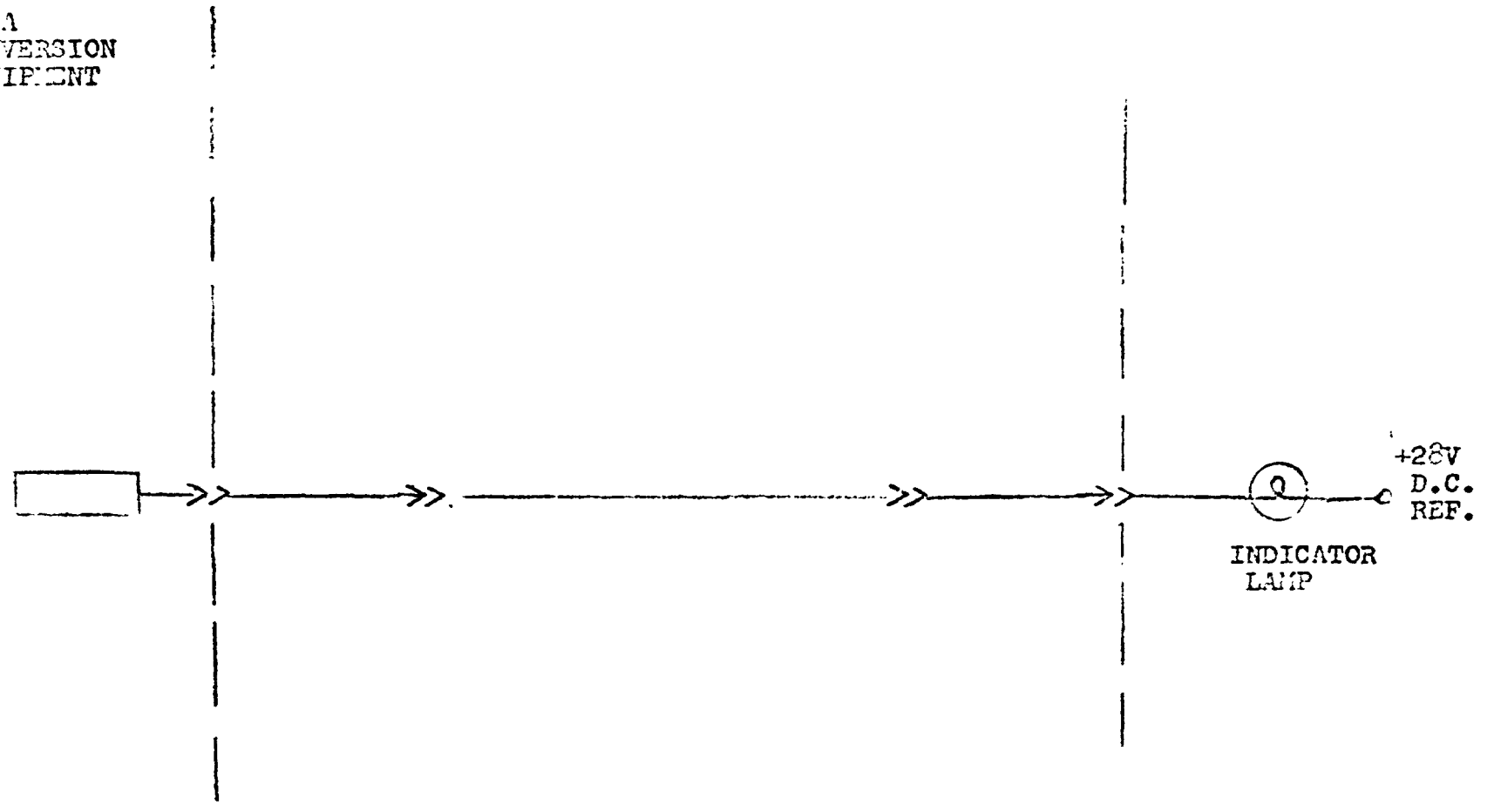
REP. NO.

F-398-8-A



CIRCUIT TYPE DØ-1A

INDICATOR LAMP

DATE 6-22-73

REV.

THE SINGER COMPANY
SIMULATION PRODUCTS DIVISION
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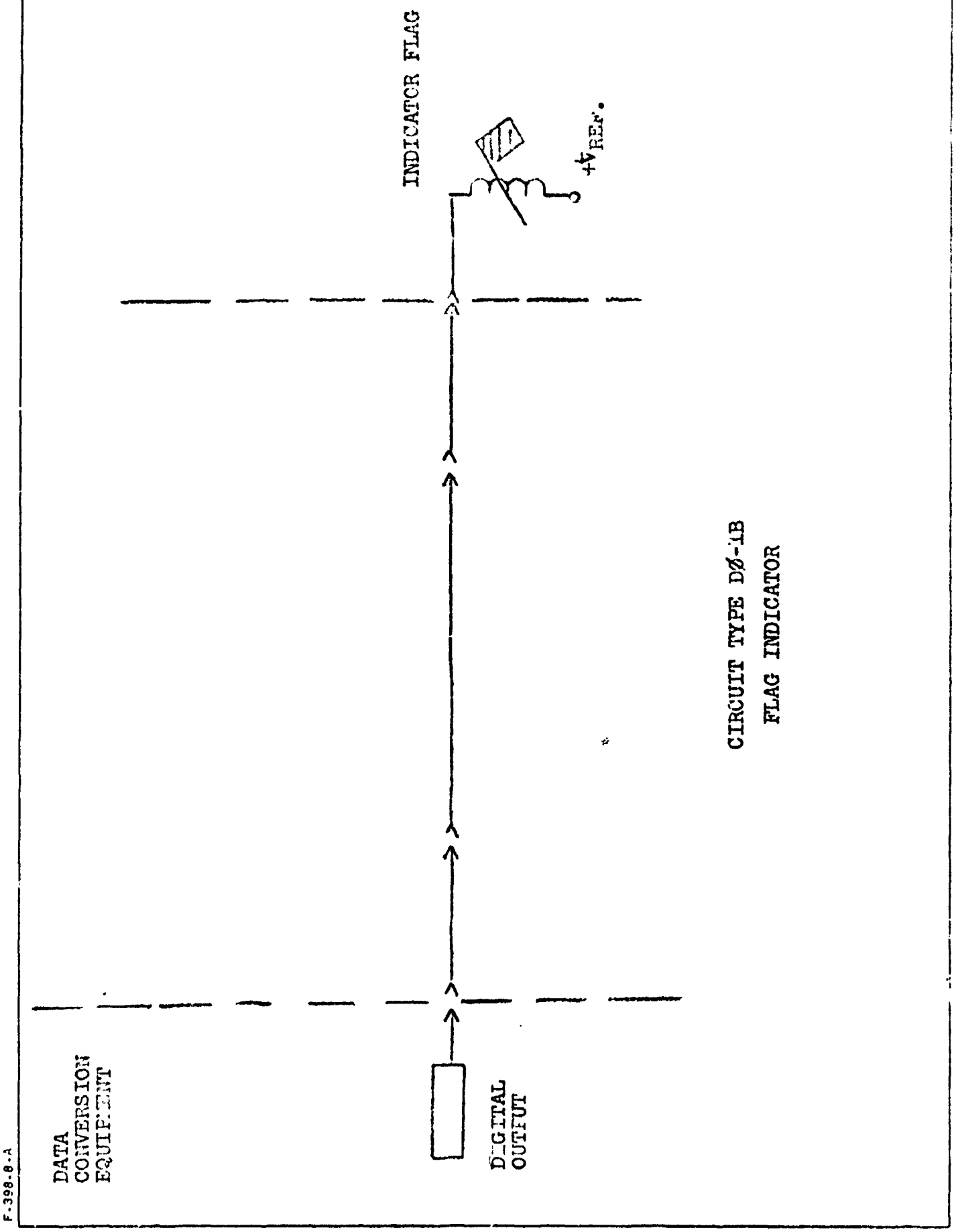
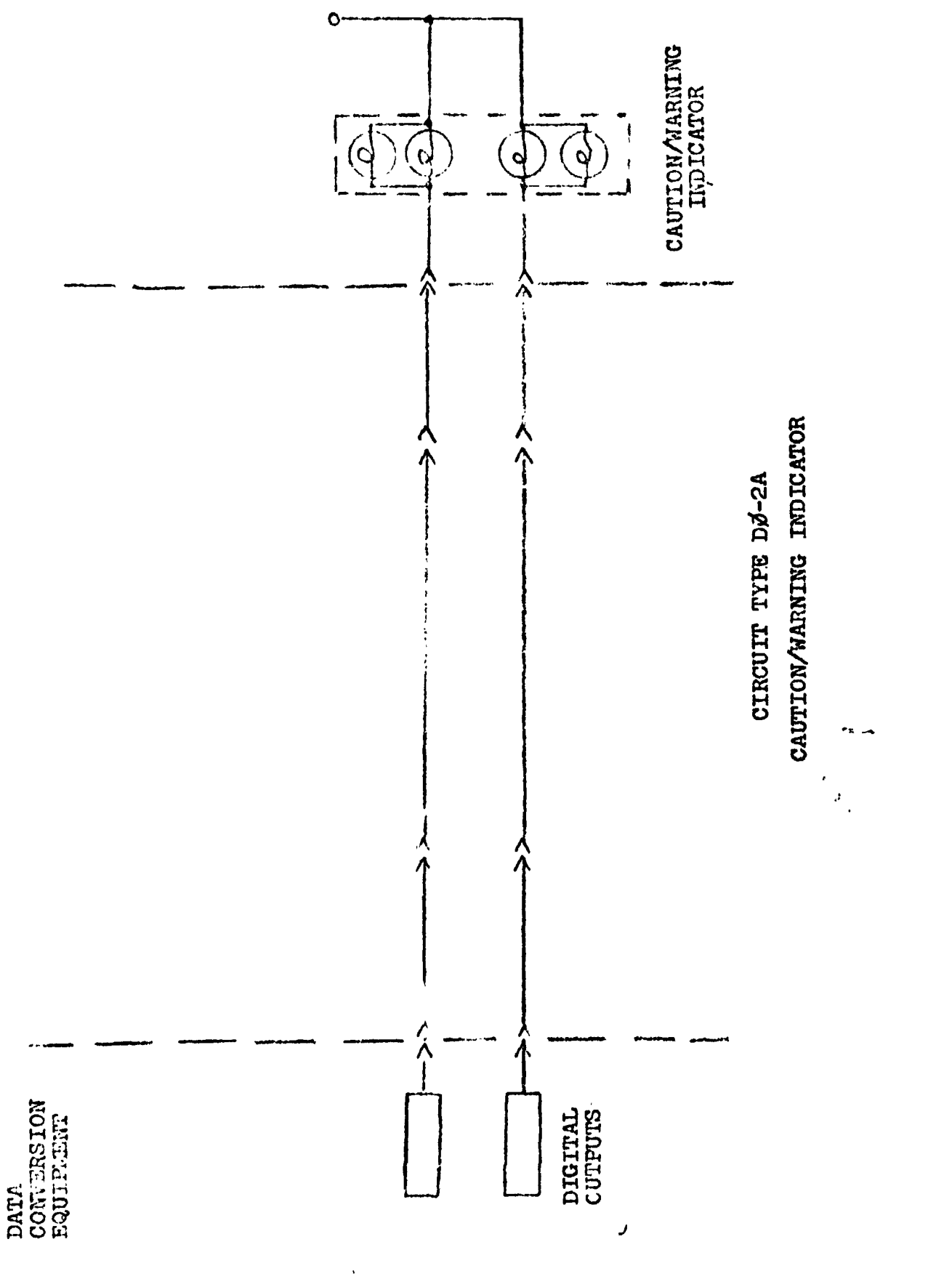
REP. NO.


INDICATOR FLAG
+V REF.
DATA CONVERSION EQUIPMENT
DIGITAL OUTPUT
CIRCUIT TYPE DØ-1B
FLAG INDICATOR
F-398-0-A


CAUTION/WARNING INDICATOR
DATA CONVERSION EQUIPMENT
DIGITAL OUTPUTS
CIRCUIT TYPE DØ-2A
CAUTION/WARNING INDICATOR

DATE 6-22-73	THE SINGER COMPANY SIMULATION PRODUCTS DIVISION	PAGE NO. B-20
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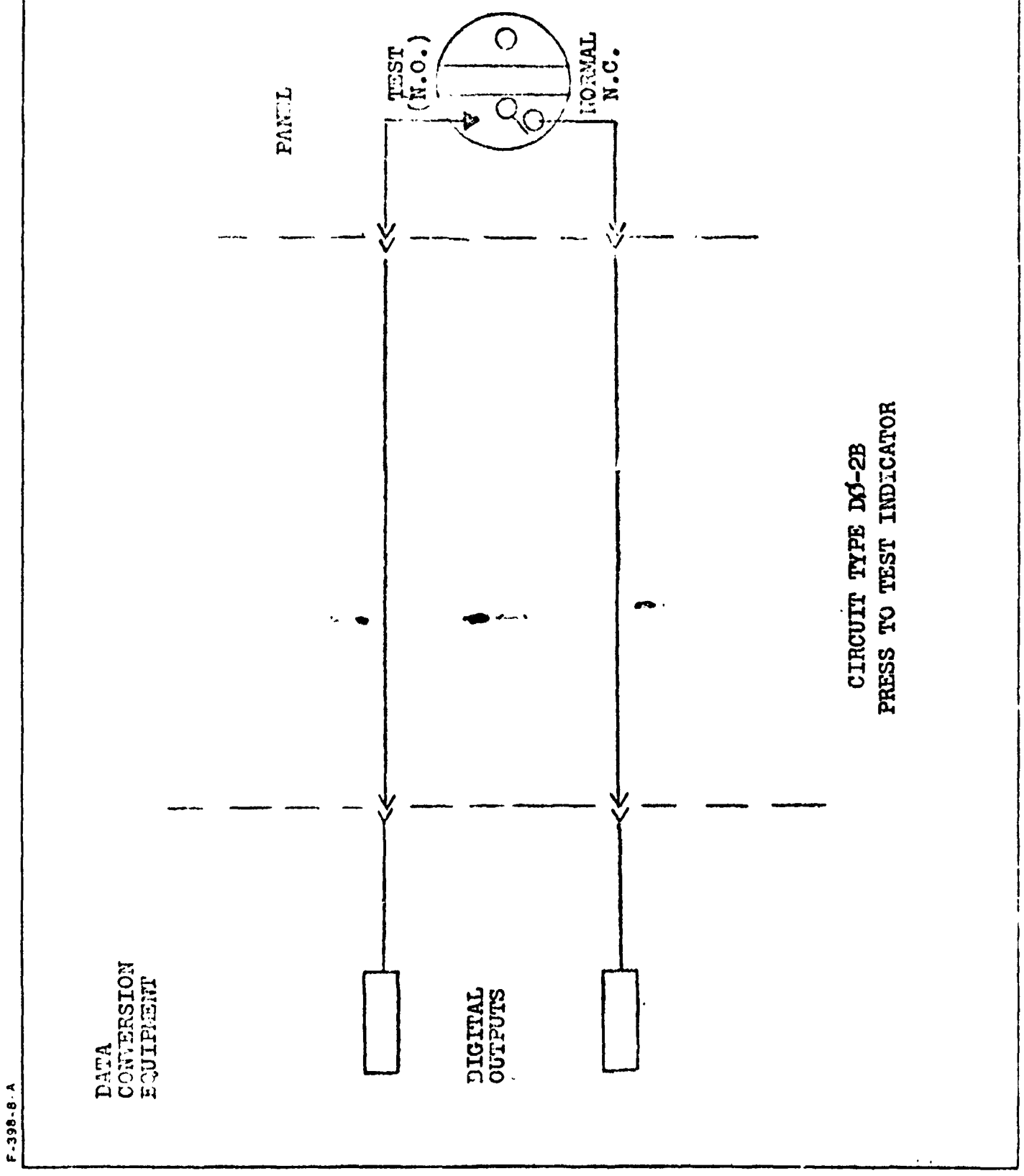
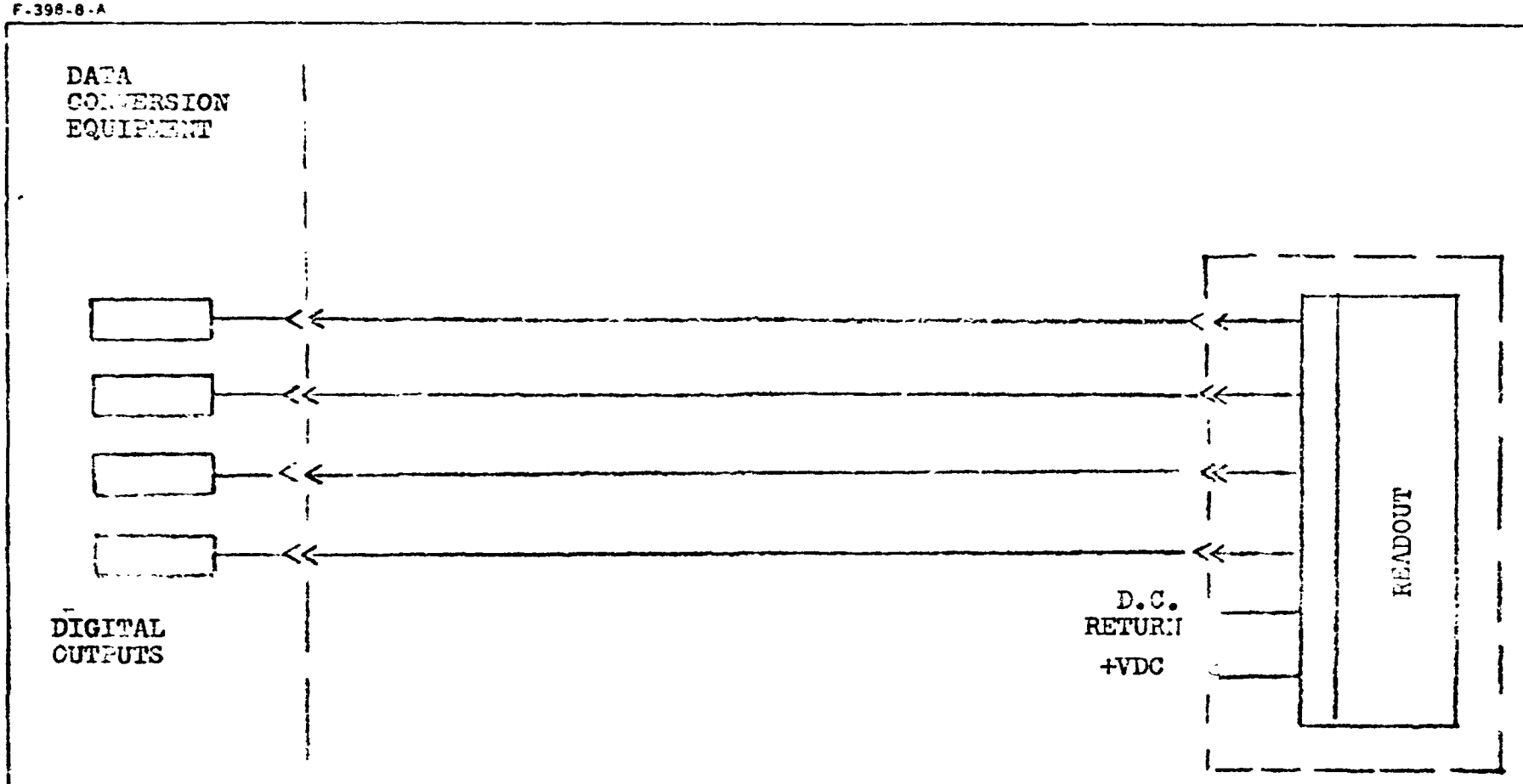


F-398-8-A

F-398-8-A



CIRCUIT TYPE DØ-4A
DIGITAL READOUT (1 DIGIT)

DATE 6-22-73
REV.

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SIMULATION PRODUCTS DIVISION
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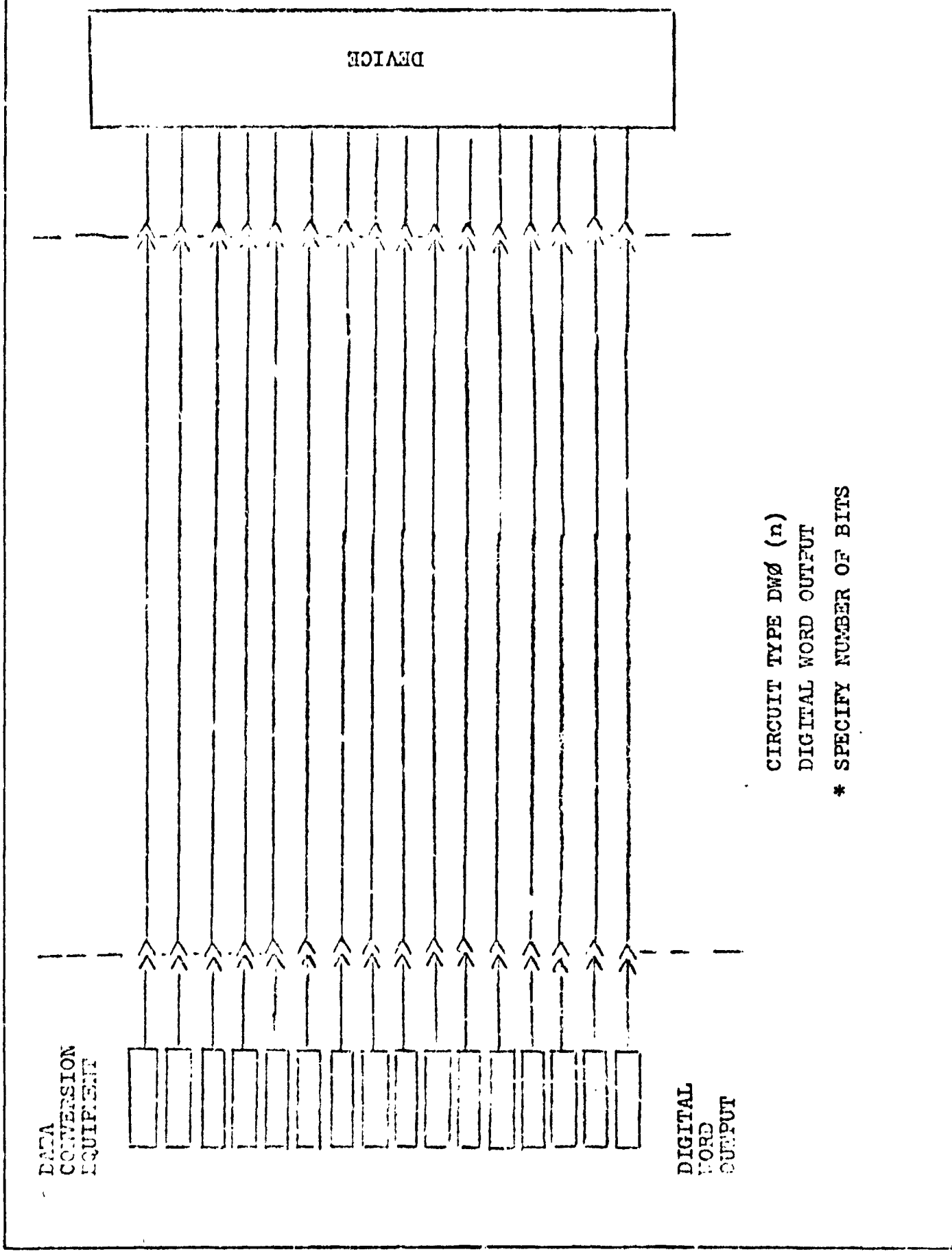
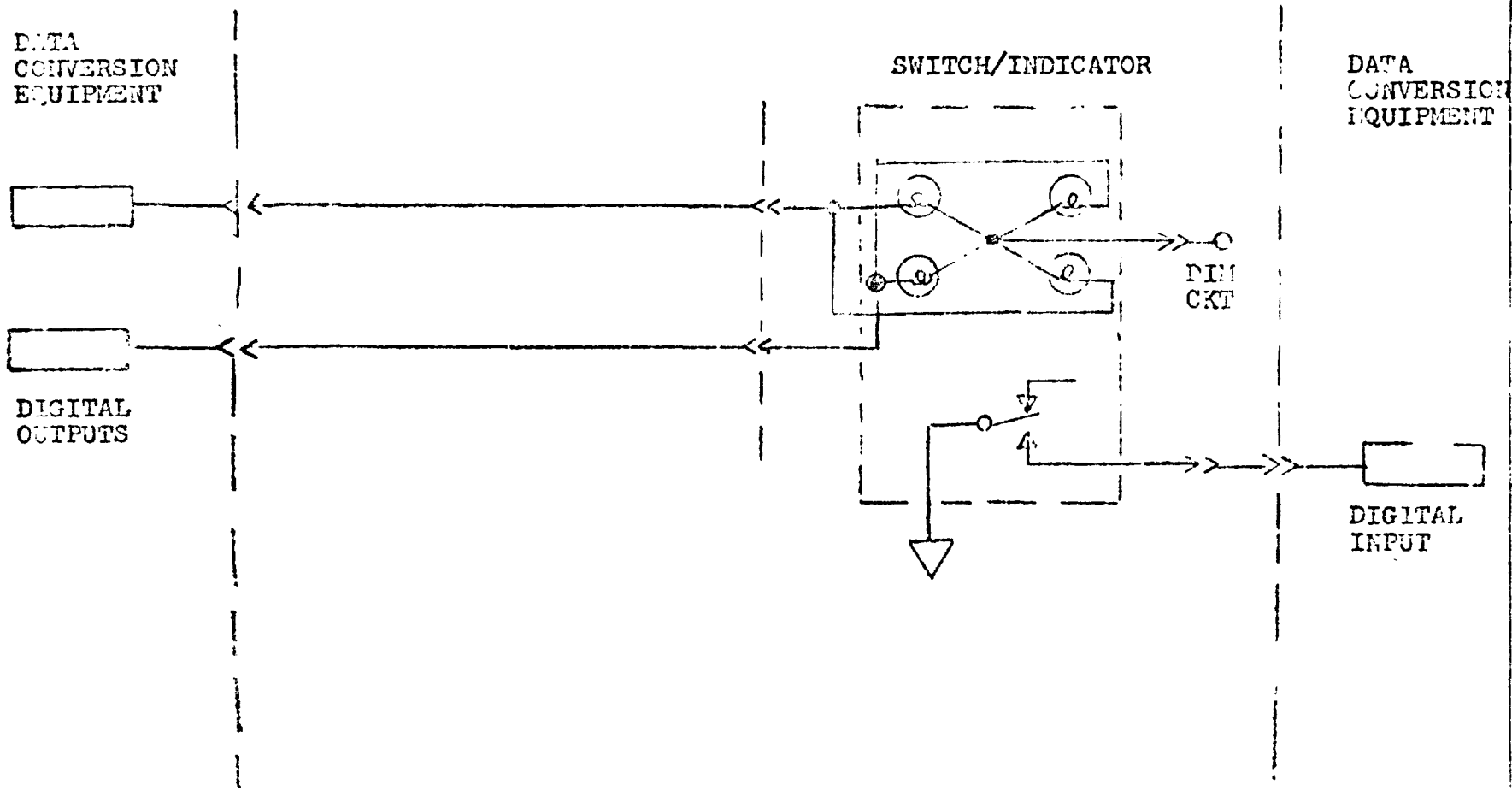
REP. NO.


DEVICE
DATA CONVERSION EQUIPMENT
DIGITAL WORD OUTPUT
CIRCUIT TYPE DWØ (n)
DIGITAL WORD OUTPUT
* SPECIFY NUMBER OF BITS

F-398-8-A

F-398-8-A



CIRCUIT TYPE DIØ-1B
ILLUMINATED MOMENTARY SWITCH WITH COMPUTER
ACTIVATED LIGHTS

DATE 6-22-73
REV.

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SIMULATION PRODUCTS DIVISION
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